Frontier Summaries and Panel Discussion:

Enabling HEP Research

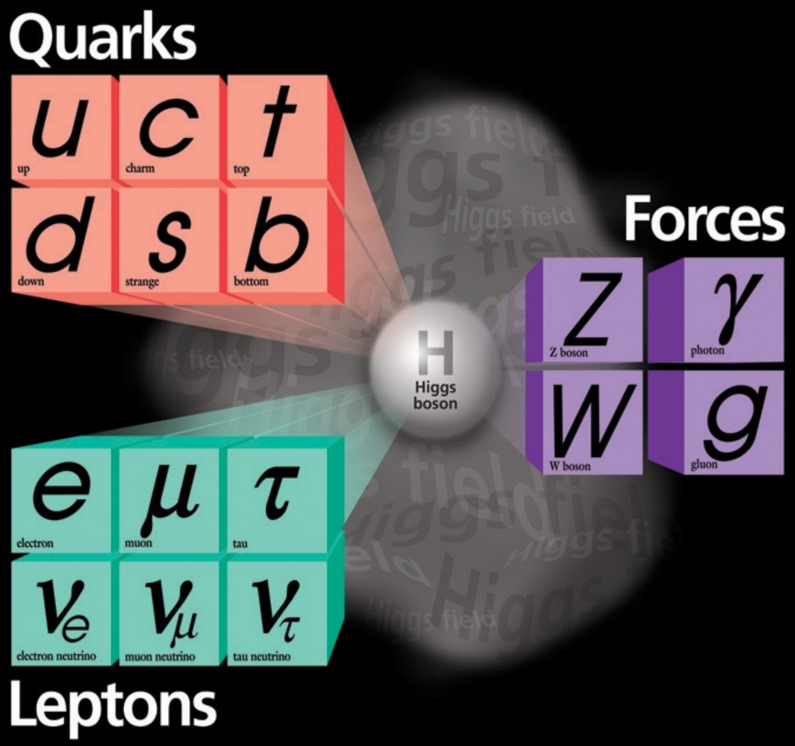
Accelerators, community engagement, computational, instrumentation, theory, underground

- Introduction
- Frontier Highlights
- Discussion and Questions

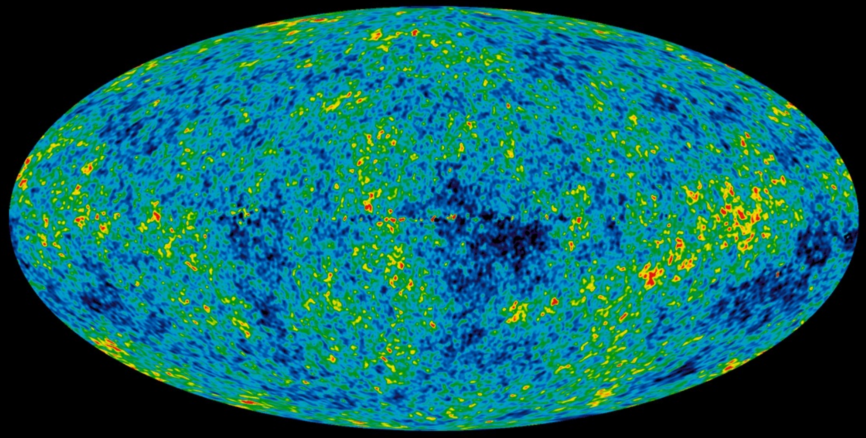
Ian Shipsey

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model

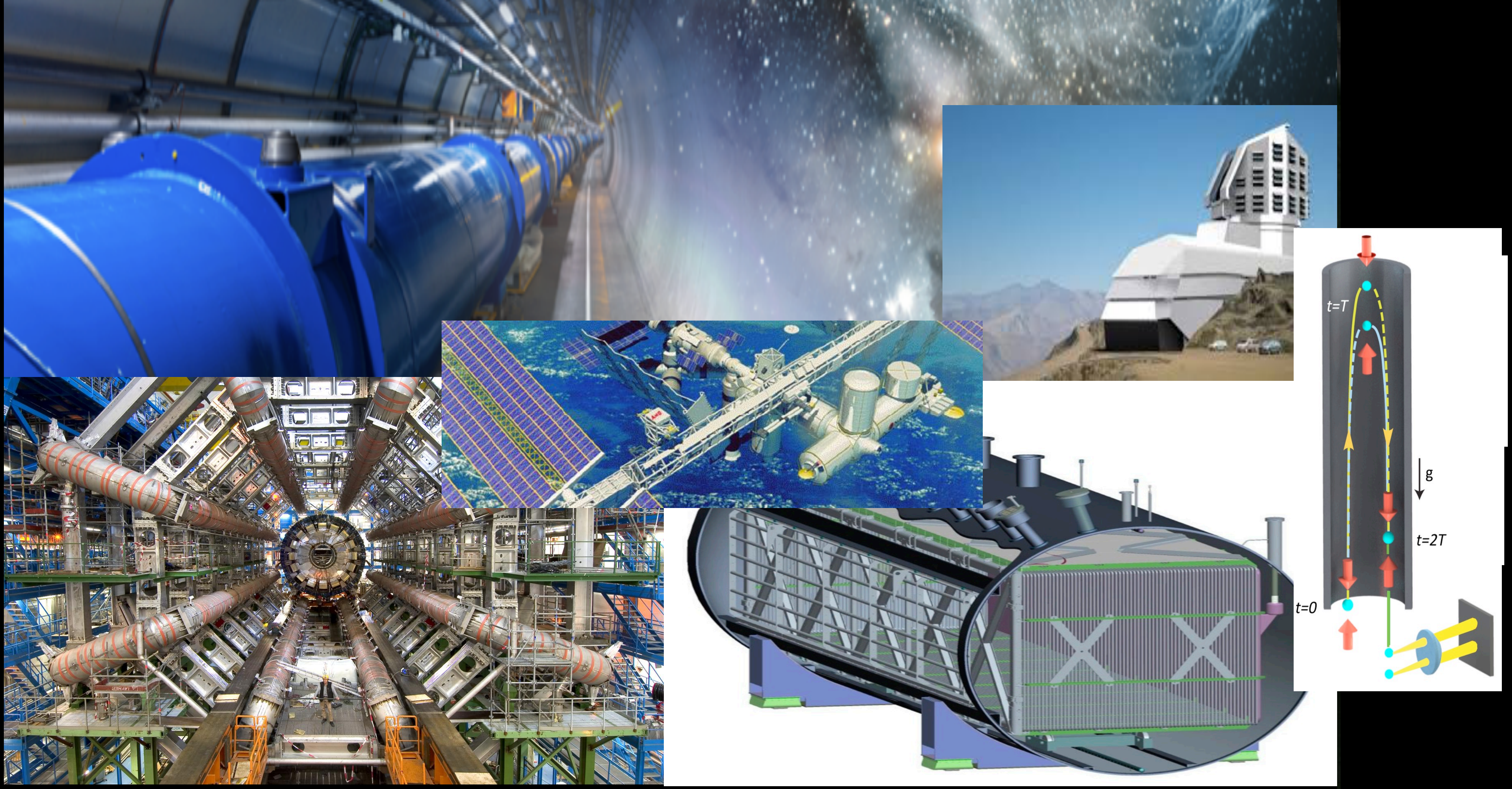


Cosmology Standard Model



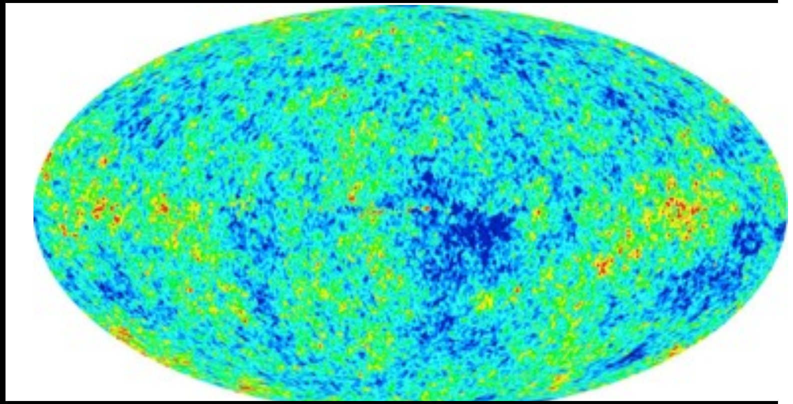
Λ_{CDM}

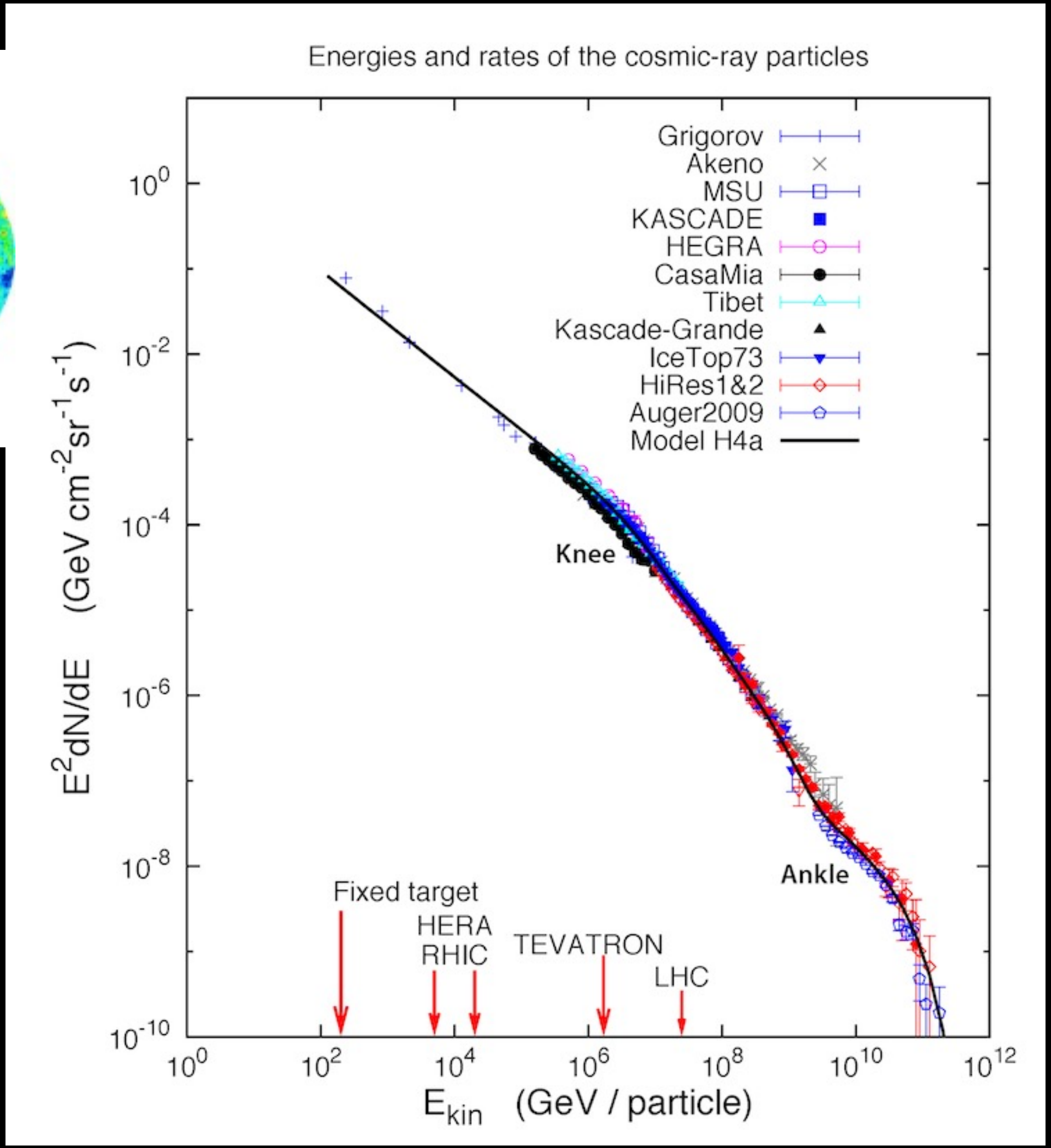
……enabled by instrumentation



Our scope is broad and we deploy many tools; theory, accelerator, non-accelerator, underground, astrophysical & cosmological, advanced detectors, quantum, AI/ML, HP computing, community engagement all have a critical role to play

Detect & Measure over 24 orders of magnitude





A Rich Spectrum of Technologies Developed by our Community

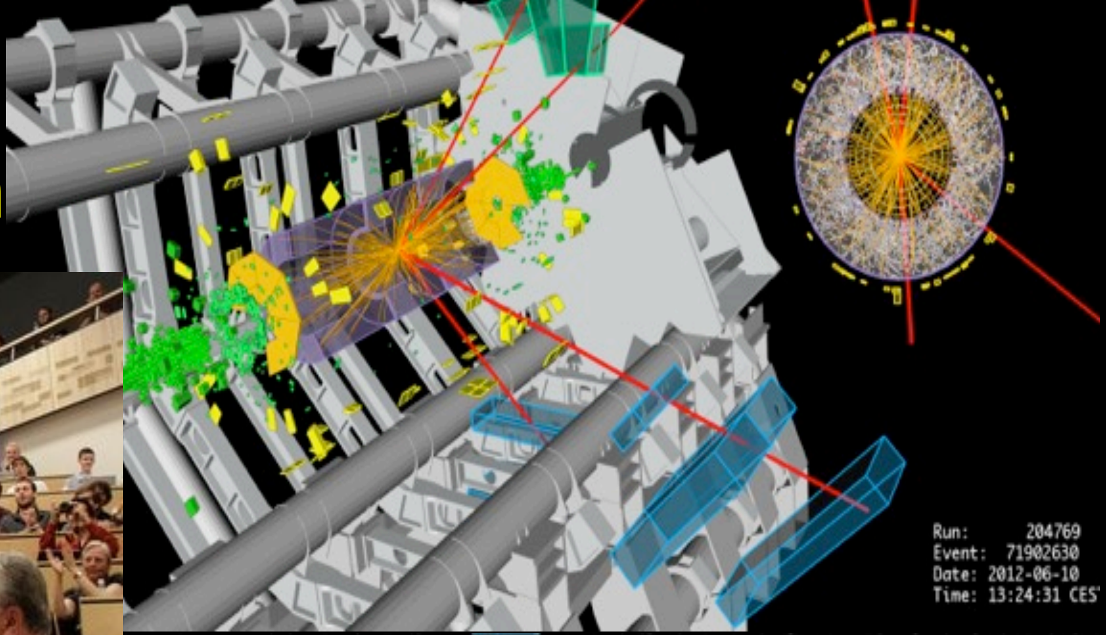
2012.7.4

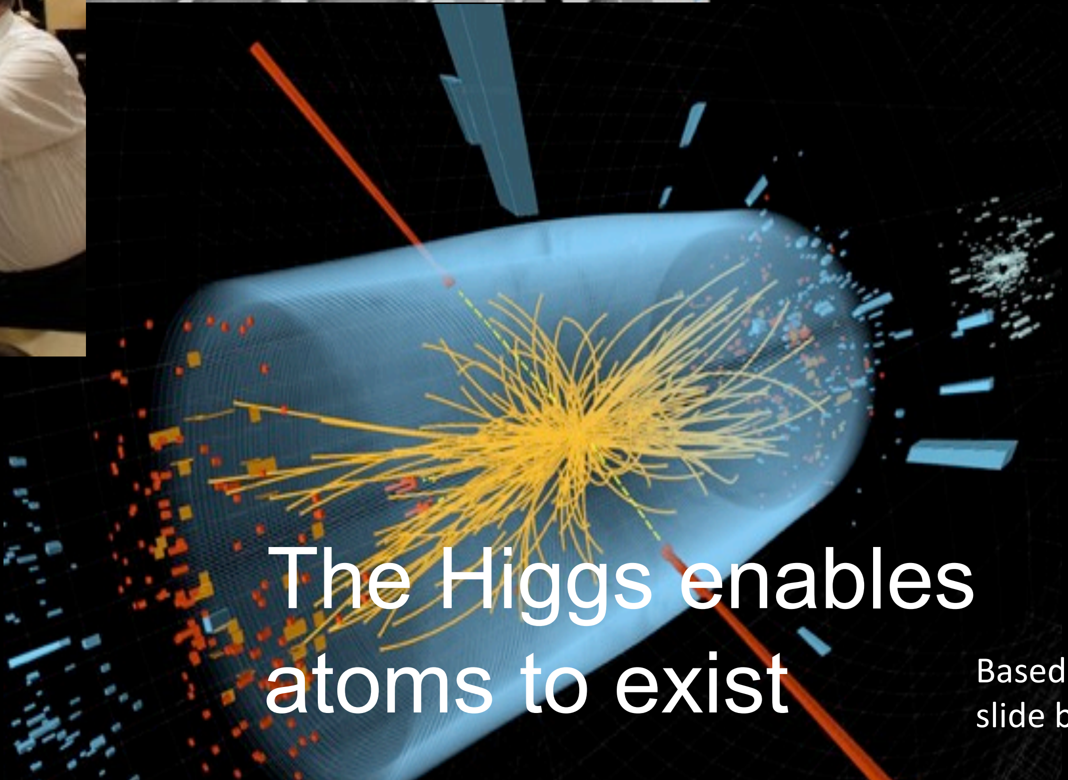
discovery of Higgs boson

theory：1964

design：1984

construction：1998

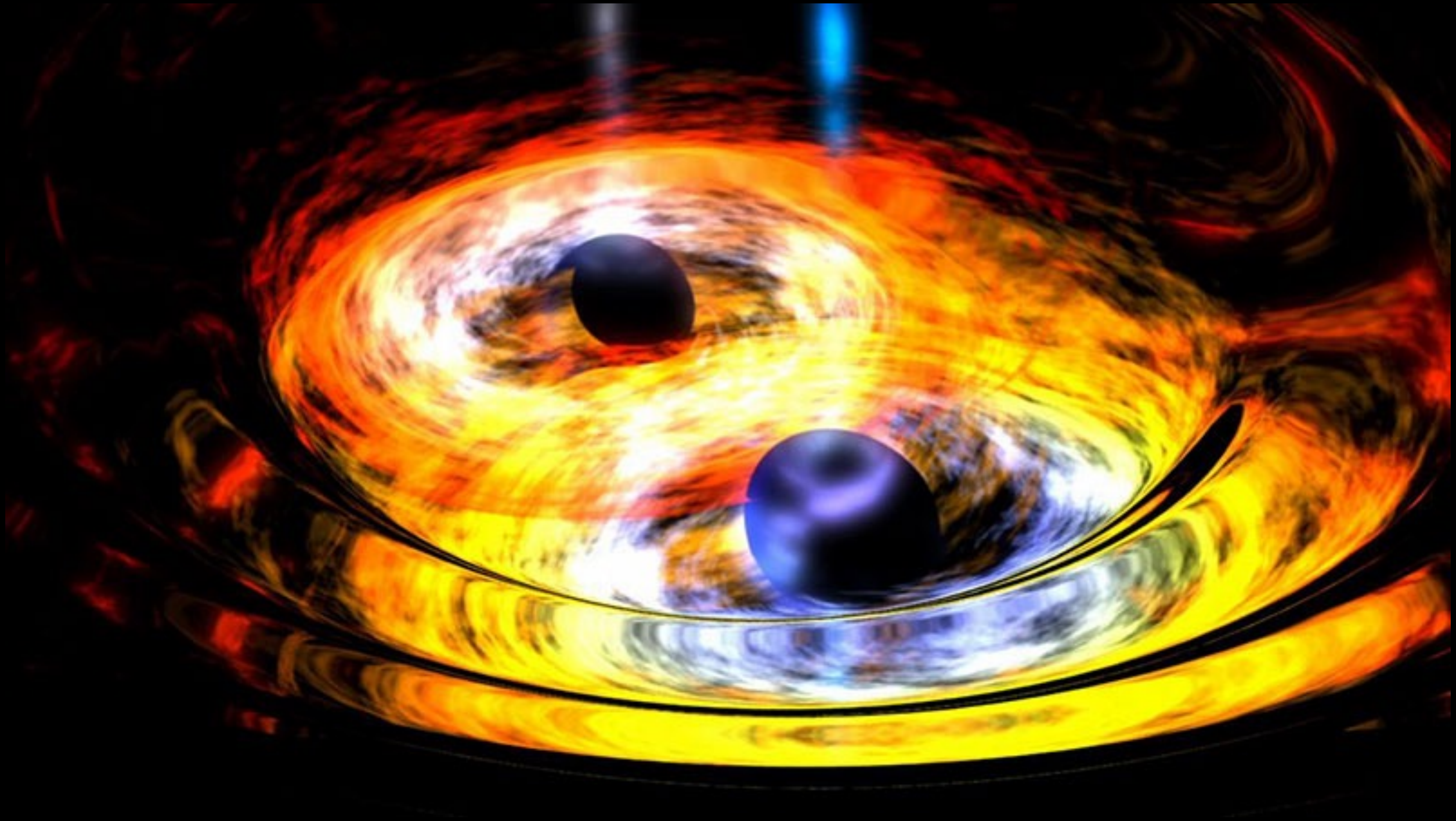




The Higgs enables atoms to exist

Based on an original slide by Hitoshi Murayama

Detection of gravitational waves
LIGO February, 2016



Opportunities for Discovery

From Marcela's talk

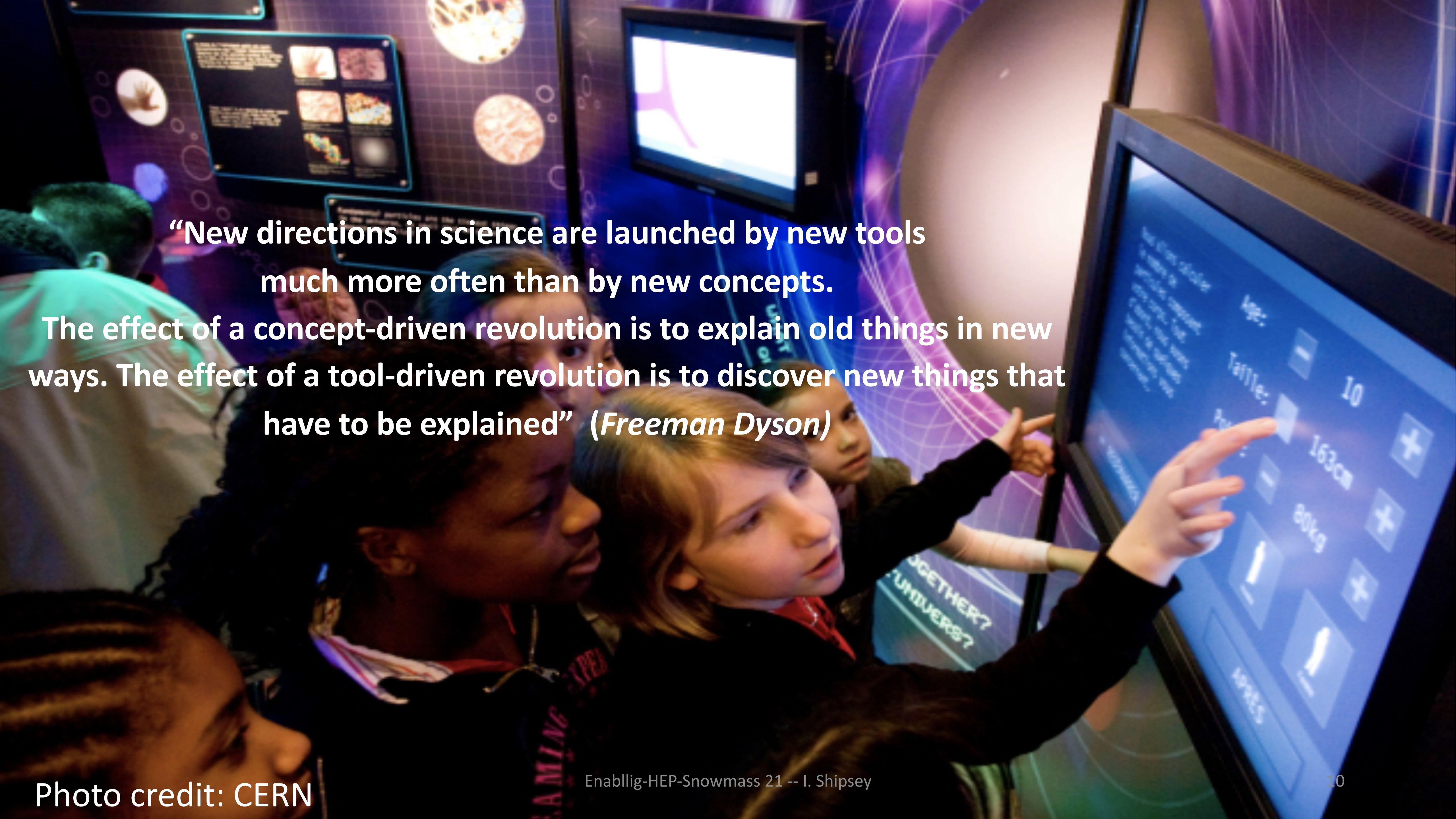
A lot of Particle Physics is Missing in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition ?
- The reason for the Hierarchy in Fermion Masses and their Flavor Structure
- The Nature of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- The cause of the Universe's accelerated expansion - Dark Energy
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

Multiple theoretical solutions – experiment must guide the way

The SM is silent about all the above, BSM physics is at the core of it all

We are very much in a data driven era for which we need new tools



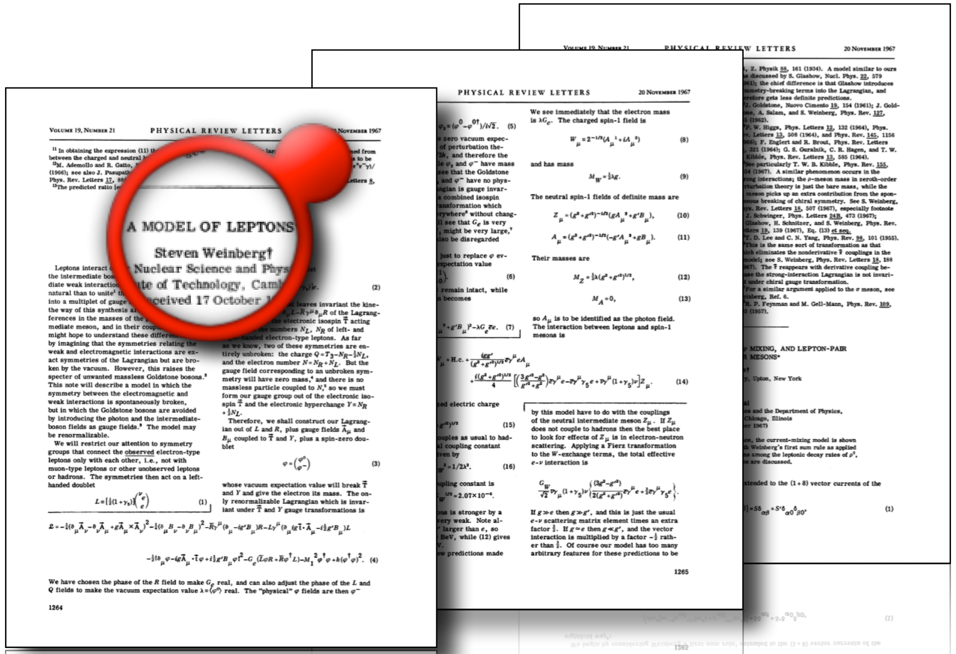
“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained” ***(Freeman Dyson)***

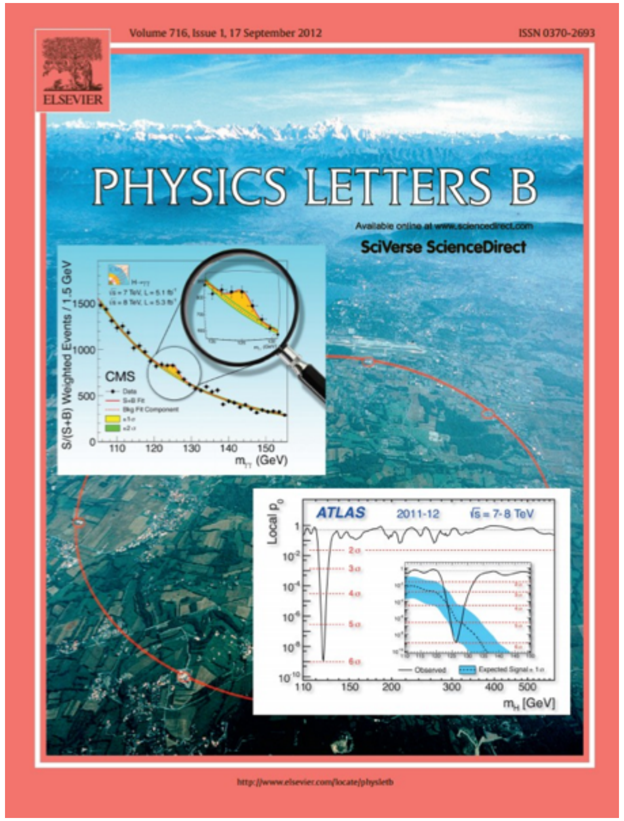
Photo credit: CERN

“Measure what is measurable, and make measurable what is not so” (*Galileo Galilei)*

Photo credit: CERN

between **1967 - 2012**





The Standard Model Guided Research

No-lose completion of the Standard Model

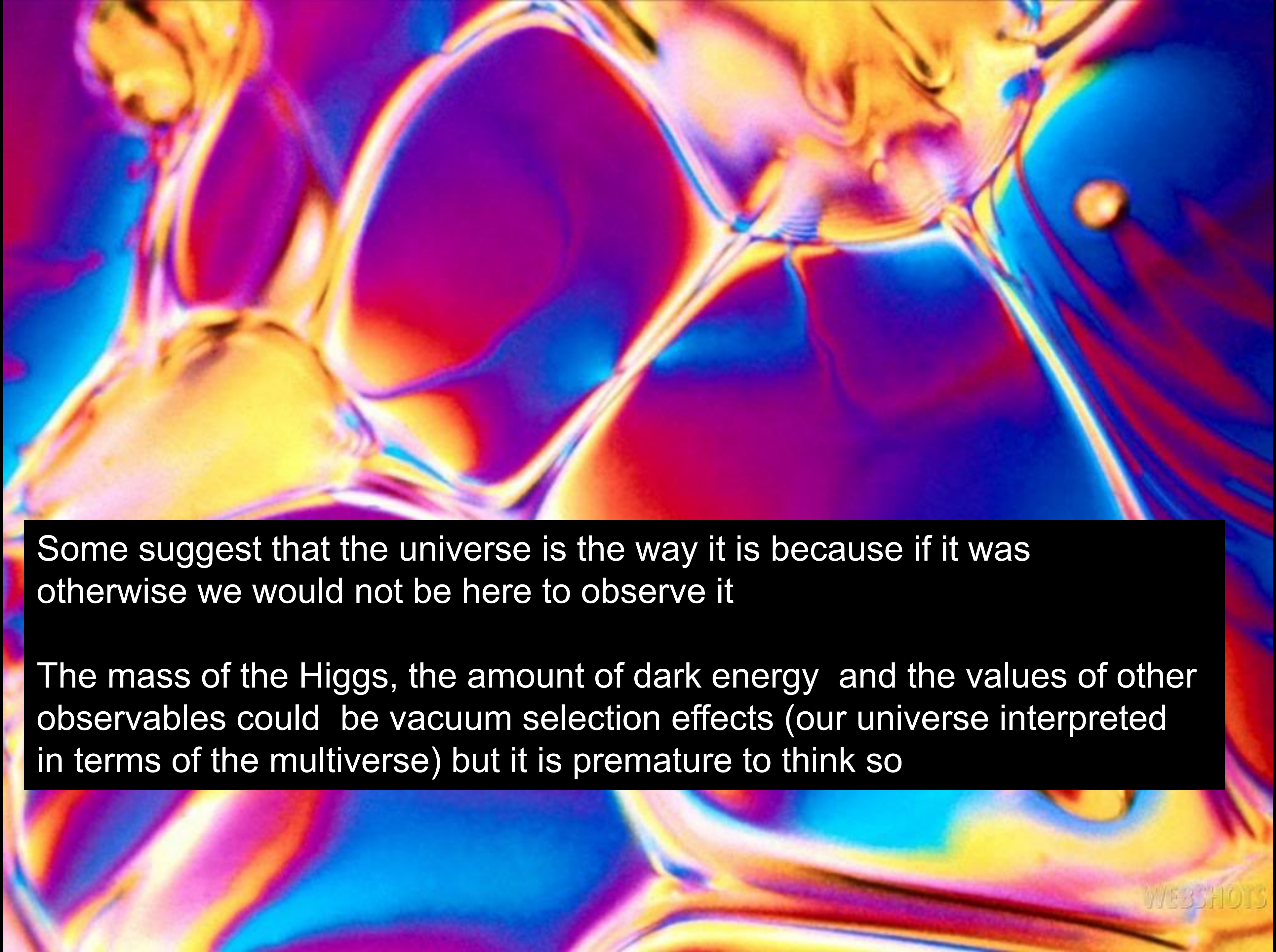
Guaranteed discoveries

W & Z	CERN SppS
Top quark	Tevatron
Higgs	LHC

No-lose completion of the Standard Model

Now that the Standard Model is complete, there are no further no-lose theorems
In principle, the Standard Model could be valid to the Planck scale. (If so much would be left unexplained.)

No guaranteed discoveries



Some suggest that the universe is the way it is because if it was otherwise we would not be here to observe it

The mass of the Higgs, the amount of dark energy and the values of other observables could be vacuum selection effects (our universe interpreted in terms of the multiverse) but it is premature to think so

Science progresses by experimentation, observation, and theory

Nobody would have predicted that slight irregularities
in black body radiation would have led to an entirely
new conception of the world in terms of quantum theory

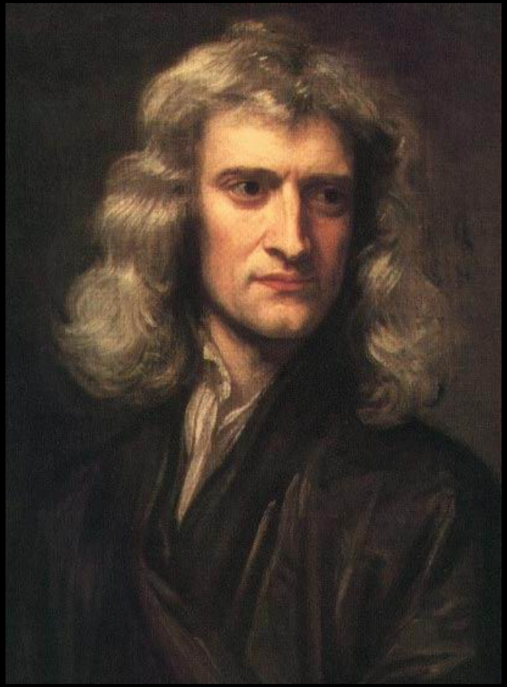
That pondering the constancy of the speed of light would have led to $E= mc^2$

That special relativity and quantum mechanics would have led to anti-matter

Experiments that explore uncharted territory, or study phenomena we do not understand with greater precision, lead to a deeper understanding of nature, the global high energy physics program does that.

The program will continue to reveal a cosmos more wonderful than we can possibly imagine.

To play a major role in this journey of discovery is the aspiration of our field



“What we know is a droplet, what we don’t know is an Ocean”

Sir Isaac Newton (1643-1727)

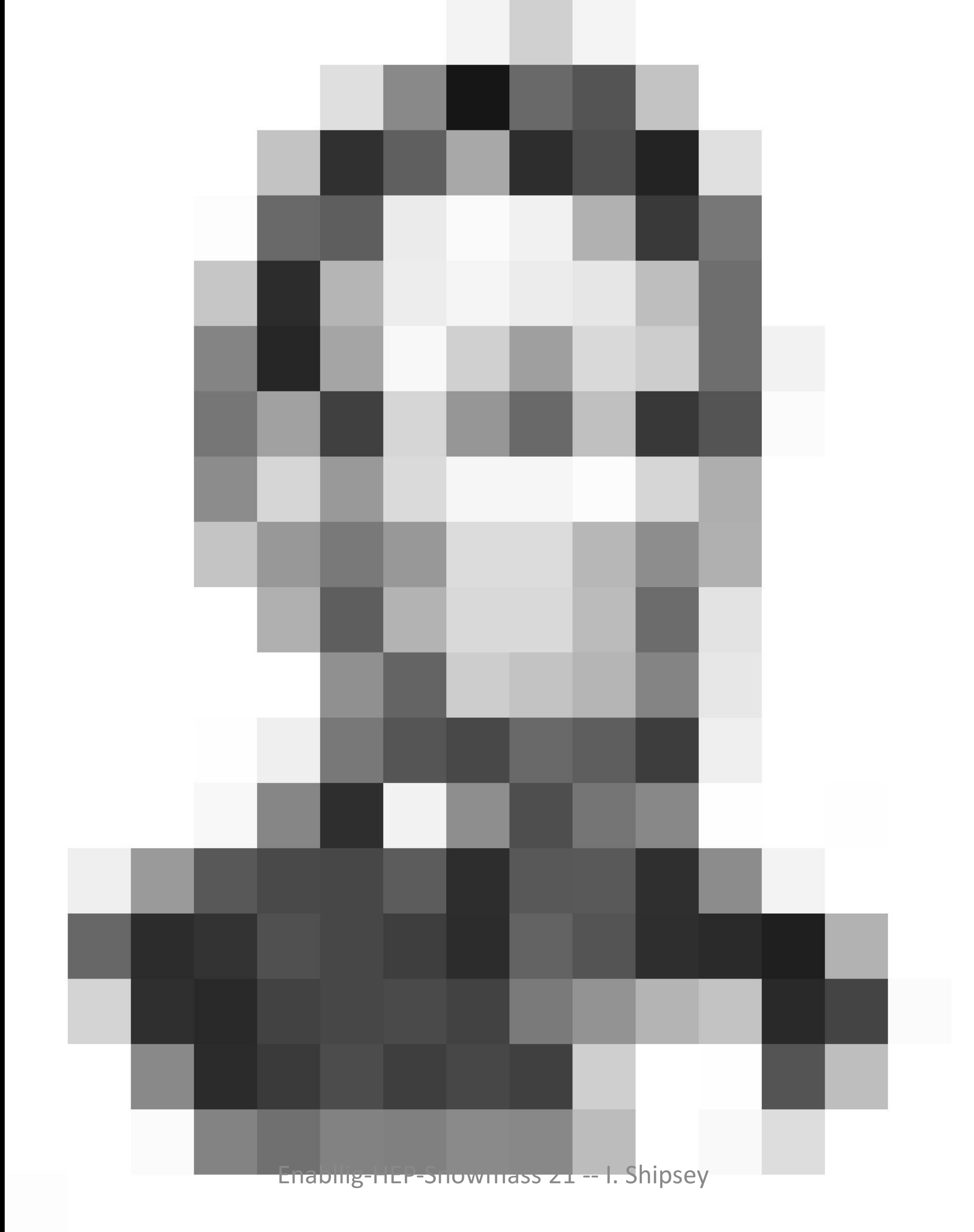
Perception & understanding *with a roadmap*

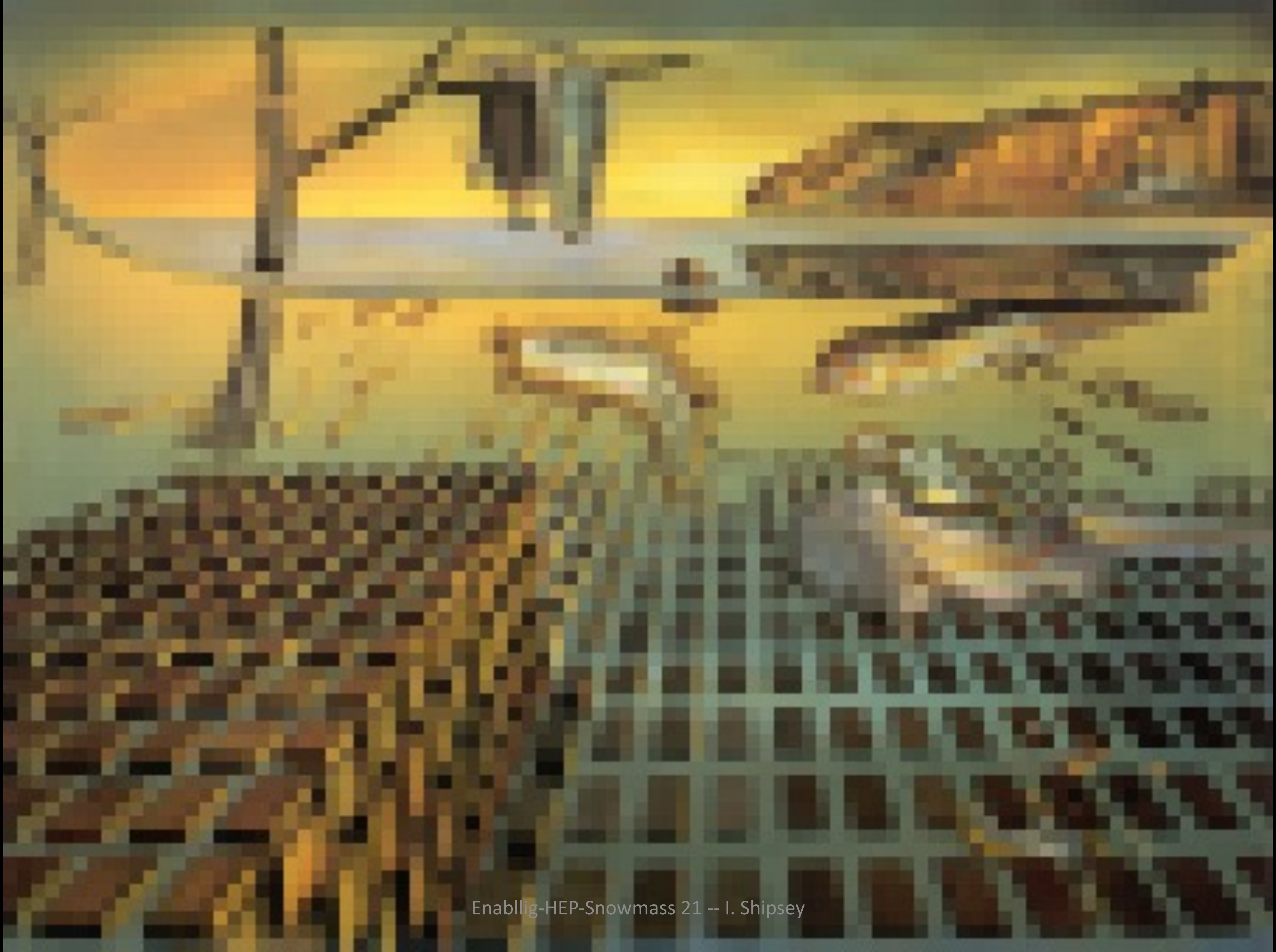
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

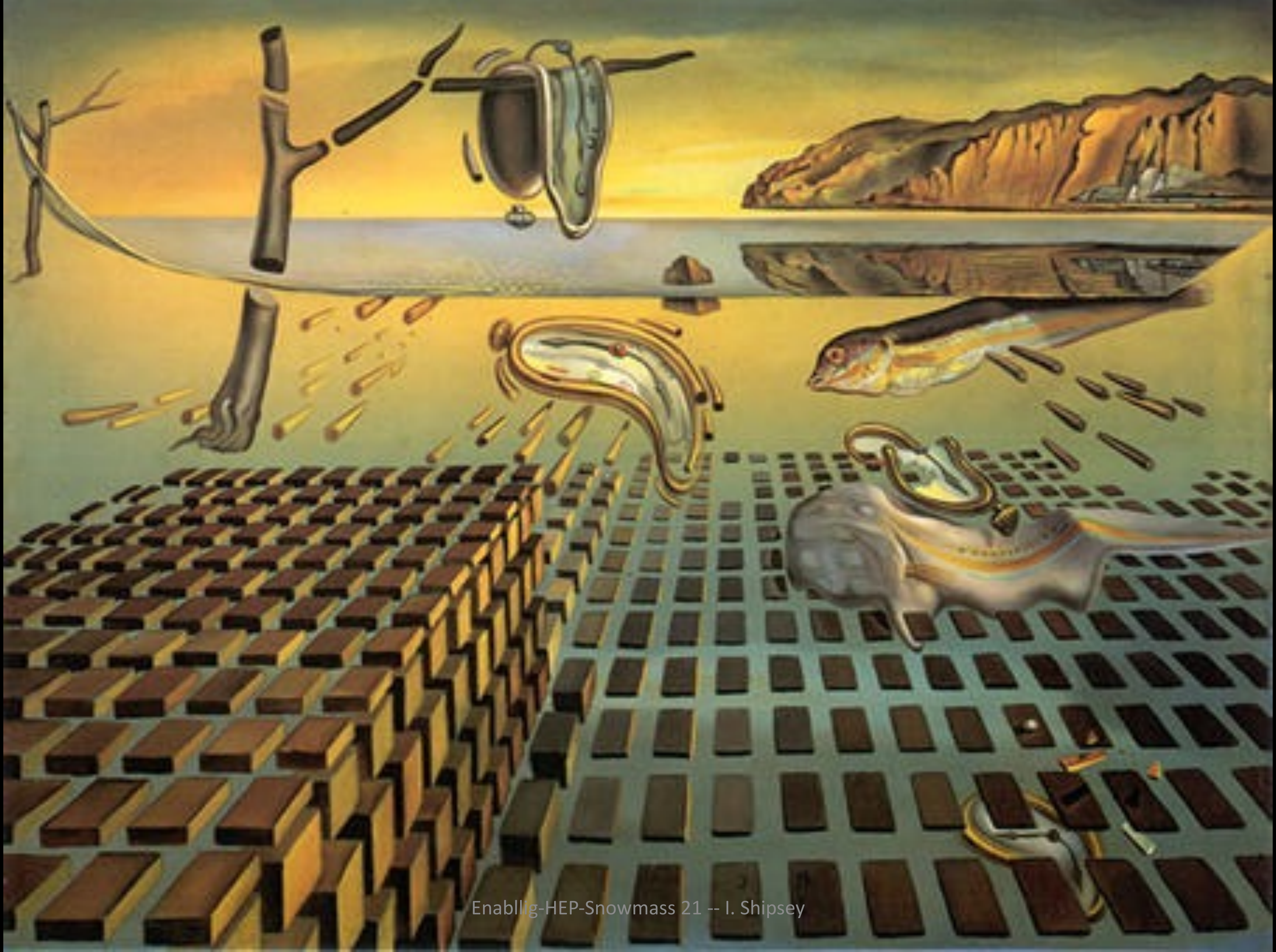
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)

Visual examples…

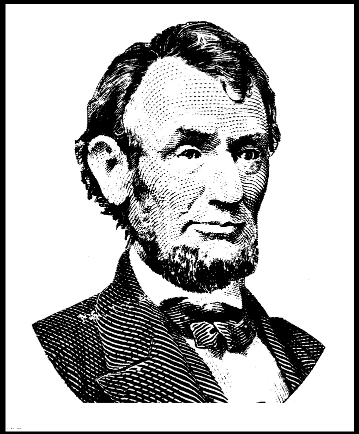






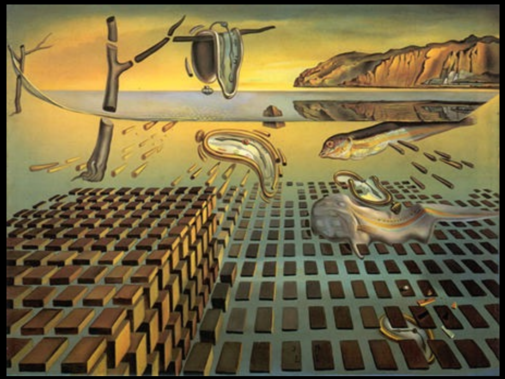
Perception & understanding

With a roadmap (theory)



(W,t,H) a little data goes a long way (top-down dominates)

w/o a roadmap (data driven)



New physics need lots of data
(bottom up dominates)

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
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precision instruments are key to discovery when exploring new territory

A PRIMER ON DETECTORS IN HIGH LUMINOSITY ENVIRONMENT

Or why you can't do physics at 10^{33}

R. Huson, L. M. Lederman and R. Schwitters
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

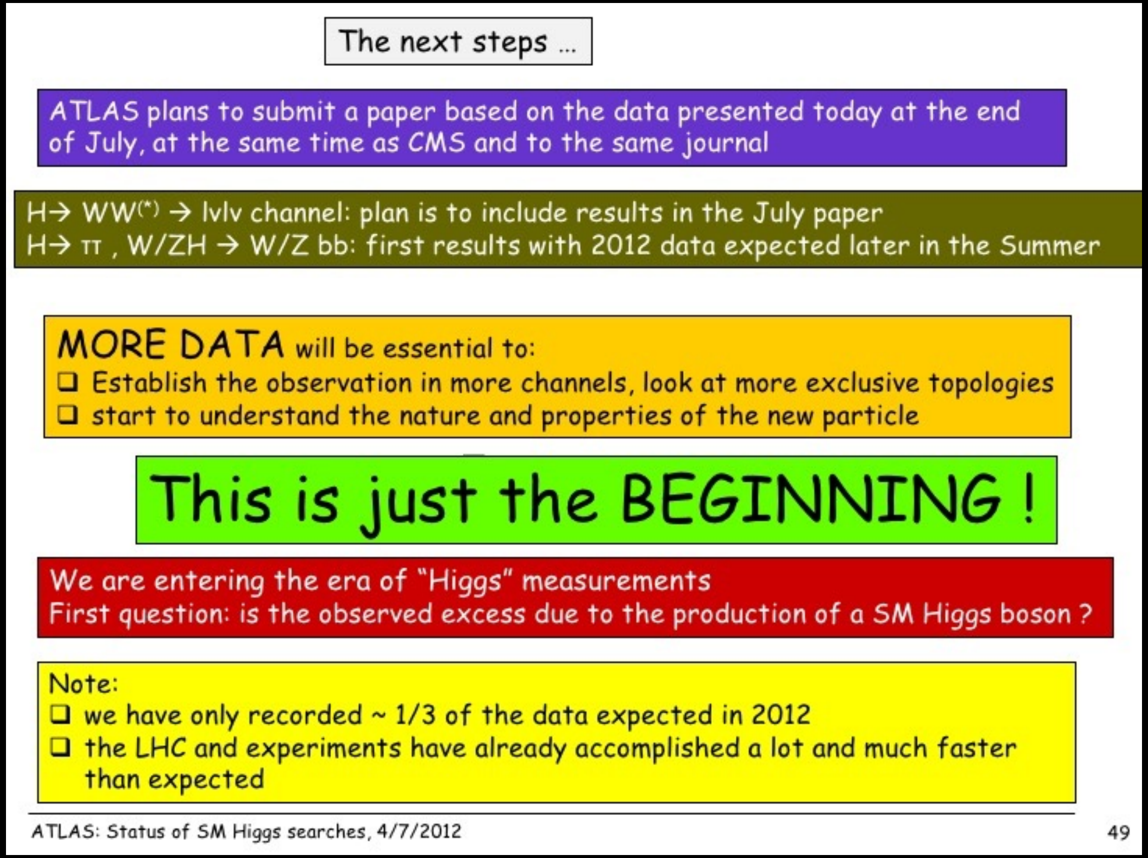
tracking efficiency; there is in fact a fair likelihood that these high multiplicities will render any of the tracking devices, as we now understand them, inoperable. PWC's have operated at ambient

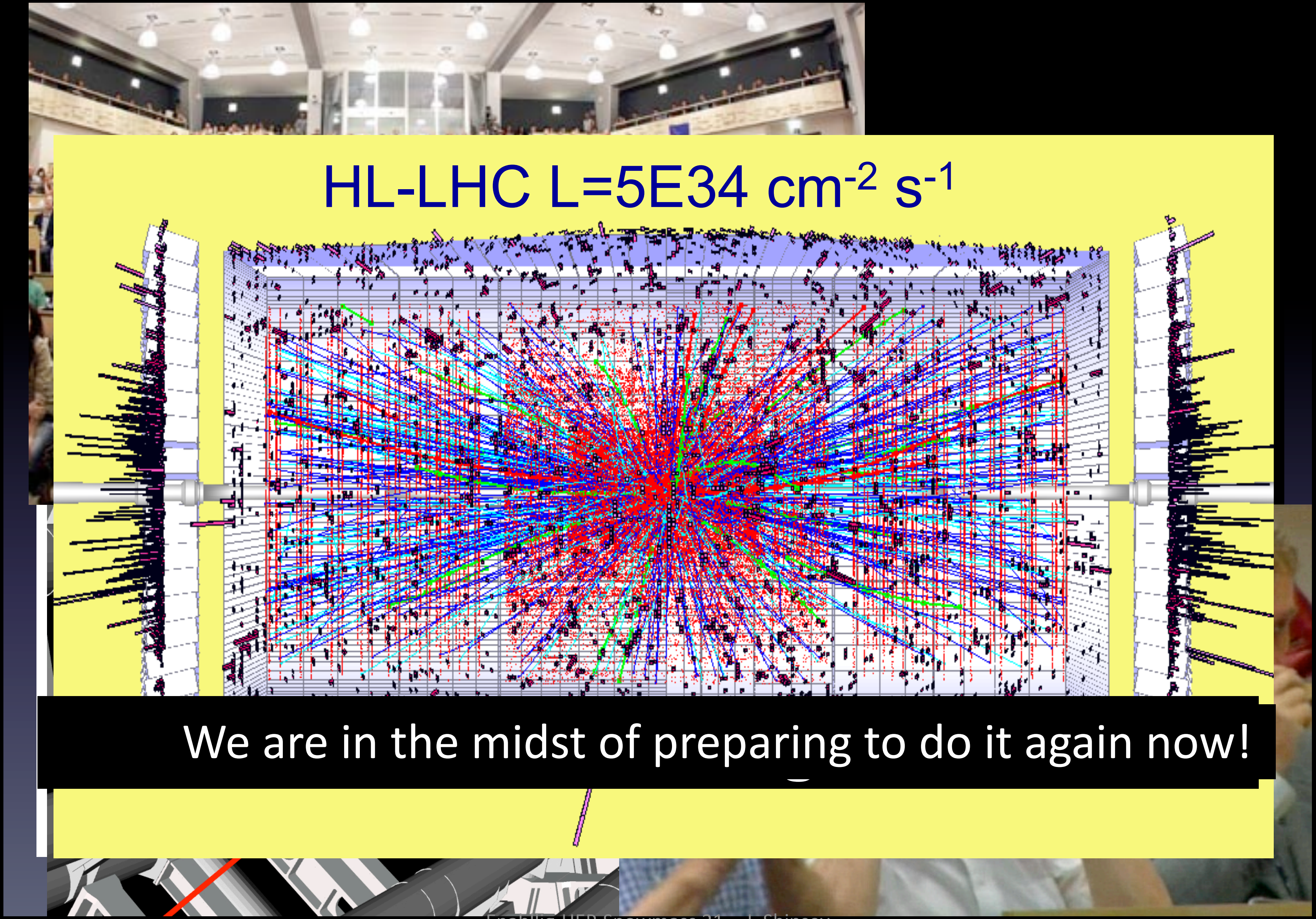
confused by the integration, but it is also clear that a large enough number of random accumulations of 10 or 20 minimum bias events can generate fake physics.

1982 SNOWMASS

program of which 10 years have already been spent. Nevertheless, (and this is the principal motivation of this paper), work must continue on decreasing the integrating time of tracking detectors, preferably without breaking the bank by infinite readout channels. Calorimetry is fundamentally ugly; a cure here would be to improve resolution, decrease integrating time and find a cheap substitute for steel.

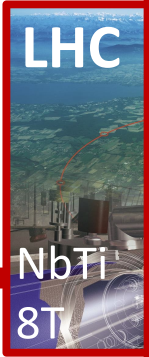
We did it!


The next steps ...
ATLAS plans to submit a paper based on the data presented today at the end of July, at the same time as CMS and to the same journal
H→ WW(*) → lvlv channel: plan is to include results in the July paper
H→ ττ , W/ZH → W/Z bb: first results with 2012 data expected later in the Summer
MORE DATA will be essential to:
❑ Establish the observation in more channels, look at more exclusive topologies
❑ start to understand the nature and properties of the new particle
This is just the BEGINNING !
We are entering the era of "Higgs" measurements
First question: is the observed excess due to the production of a SM Higgs boson ?
Note:
❑ we have only recorded ~ 1/3 of the data expected in 2012
❑ the LHC and experiments have already accomplished a lot and much faster than expected
ATLAS: Status of SM Higgs searches, 4/7/2012
49


HL-LHC L=5E34 cm-2 s-1
We are in the midst of preparing to do it again now!

Current flagship (27km)

impressive programme up to 2040



ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

European Strategy Update

Since last Snowmass clearer understanding of timescales for accelerator frontier @ CERN

energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

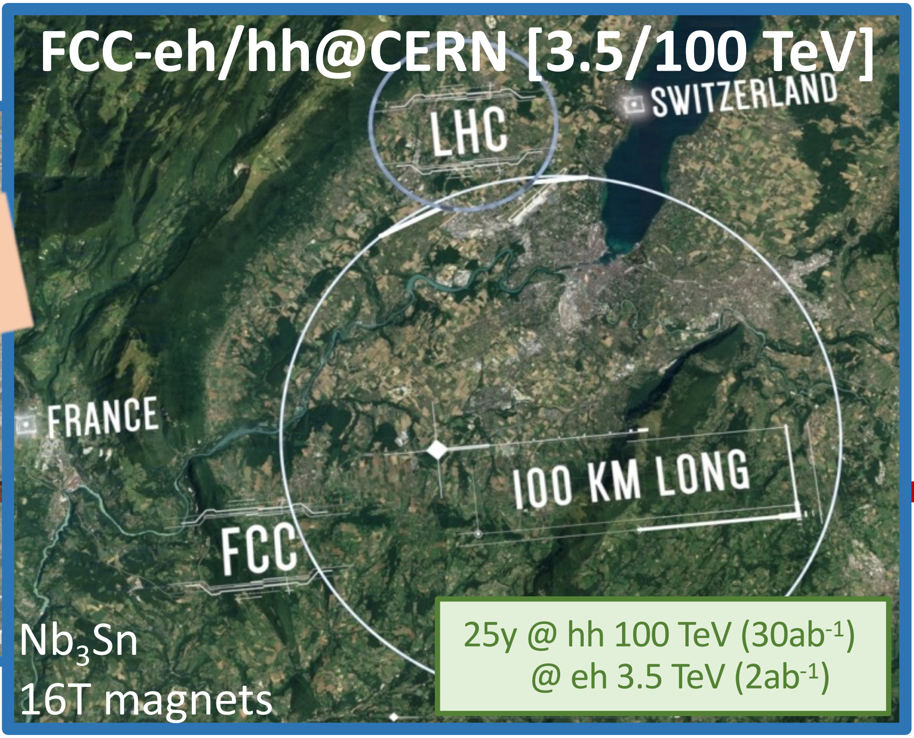
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491



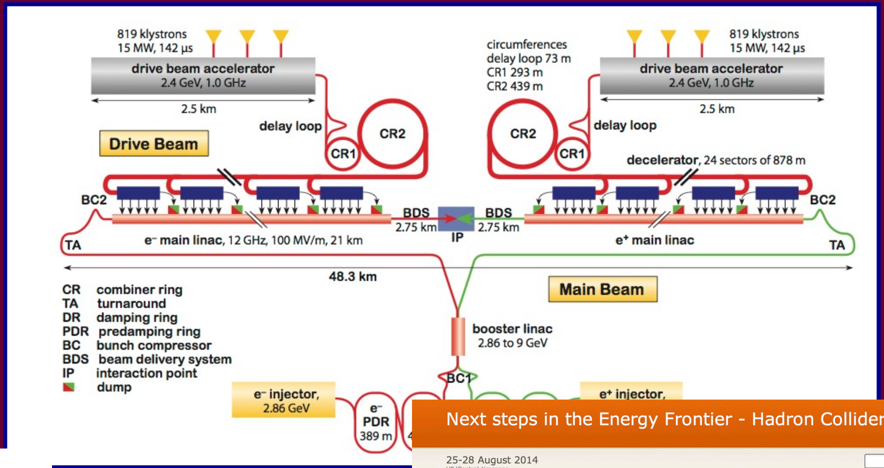
numbers assume 2 IPs for each collider (only one for FCC-eh)

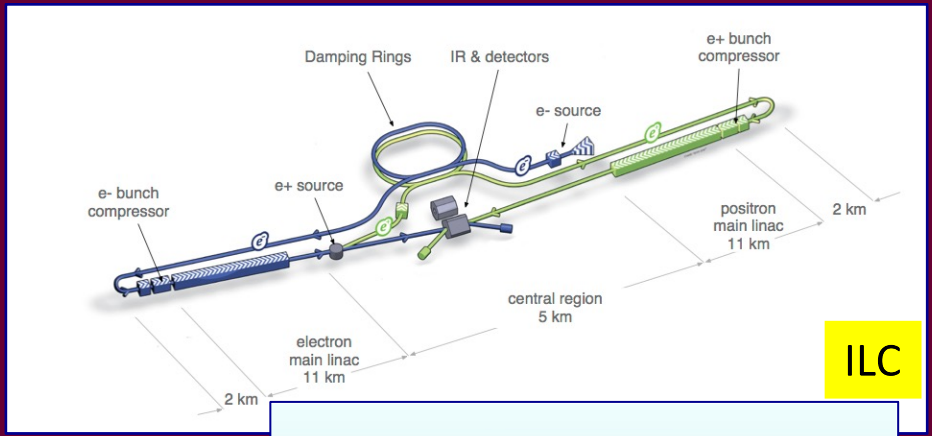
European Strategy Update

by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

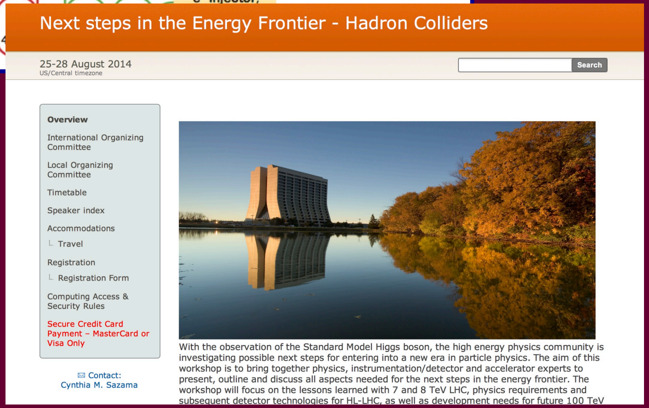
Accelerator frontier





International
MUON Collider
Collaboration

https://muoncollider.web.cern.ch


Next steps in the Energy Frontier - Hadron Colliders

25-28 August 2014

US/Central timezone

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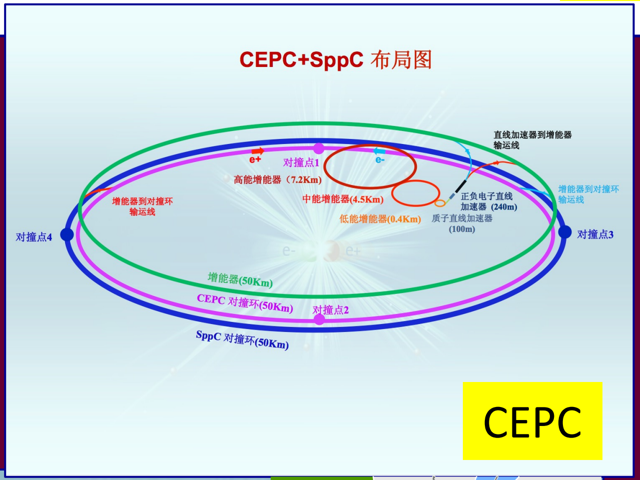
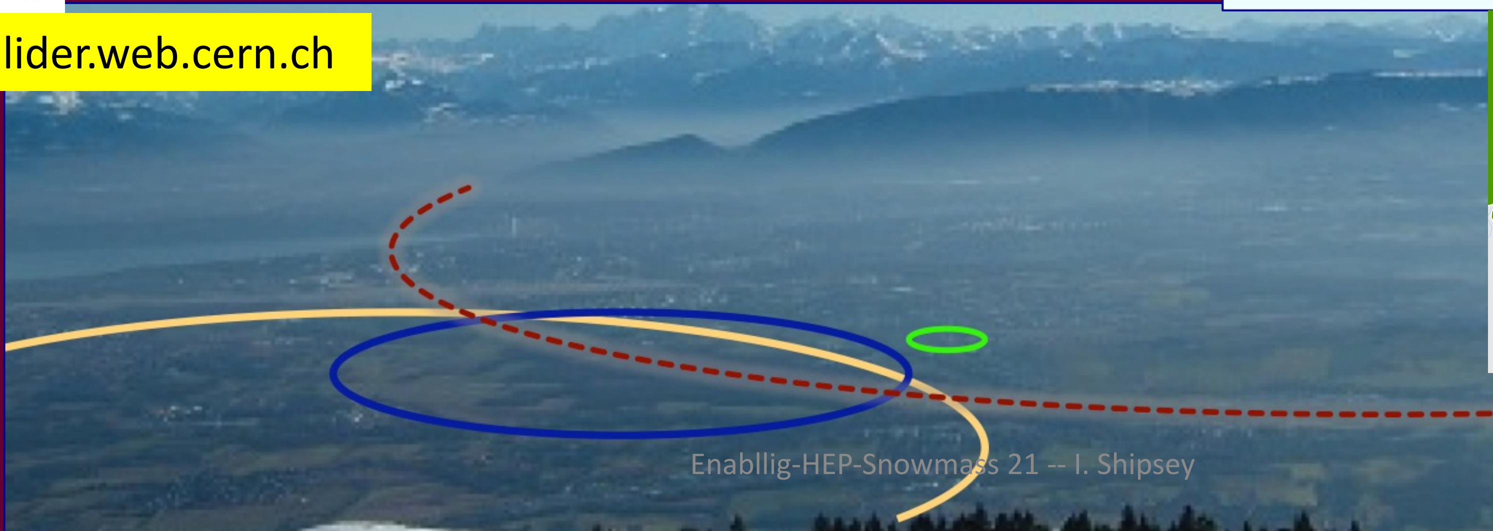
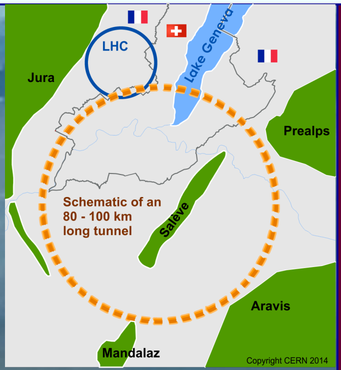
Contact:
Cynthia M. Sazama

With the observation of the Standard Model Higgs boson, the high energy physics community is investigating possible next steps for entering into a new era in particle physics. The aim of this workshop is to bring together physics, instrumentation/detector and accelerator experts to present, outline and discuss all aspects needed for the next steps in the energy frontier. The workshop will focus on the lessons learned with 7 and 8 TeV LHC, physics requirements and subsequent detector technologies for HL-LHC, as well as development needs for future 100 TeV







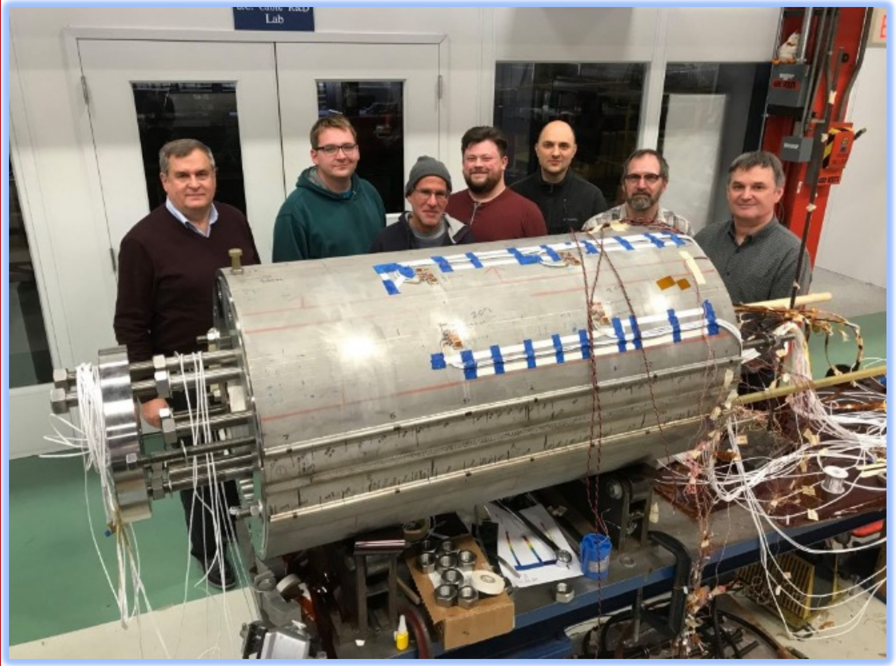
Since Snowmass 2013 exciting progress at accelerator frontier

Accelerator Technology World Records

31.5 MeV/m with beam

Superconducting RF technology new heights – already in use in X-ray sources, waiting for collider application/ILC

Magnets road to 16 T

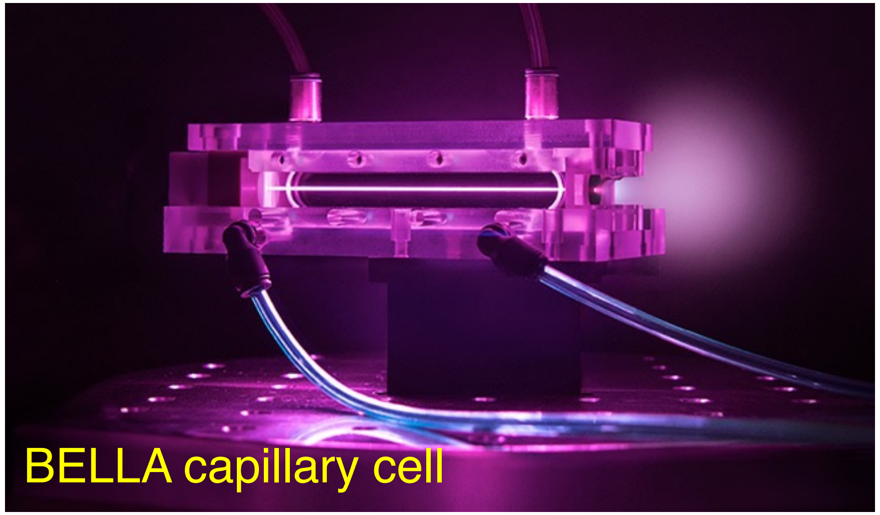


14.5 T dipole by the US Magnet Development Program - stepping stone toward ***hh*** or ***μμ*** machine

Since Snowmass 2013 exciting progress at accelerator frontier

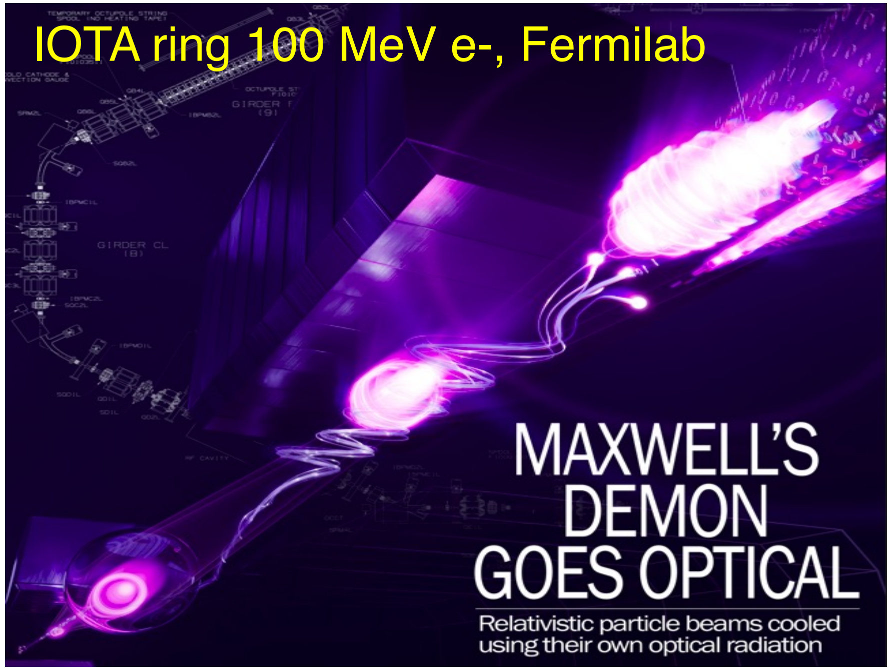
Beam Physics Breakthroughs

8 GeV gain over 20 cm



Two decades of breakthroughs in plasma acceleration - can they be turned into practical accelerators? colliders??

Optical Stochastic Cooling



May be as revolutionary as (original) stochastic cooling (Nobel prize, *W*/*Z*-discovery, 1984)

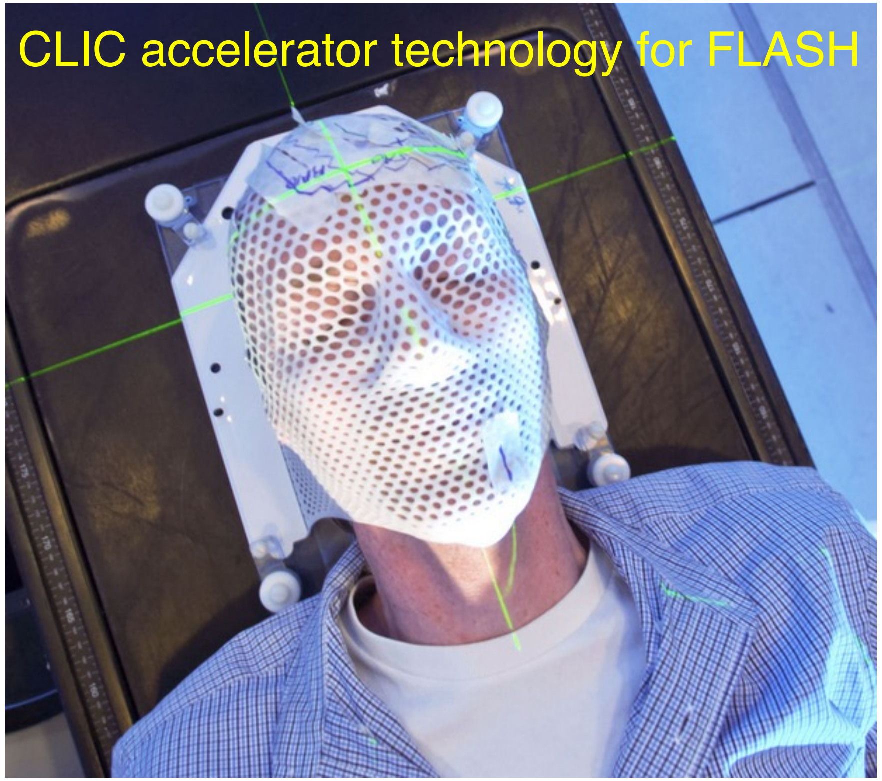
Beams for Society

Since Snowmass 2013 exciting progress at accelerator frontier

X-ray sources save lives

COVID virus studies and drug development at modern light sources provides critical paths to keep us safe and healthy

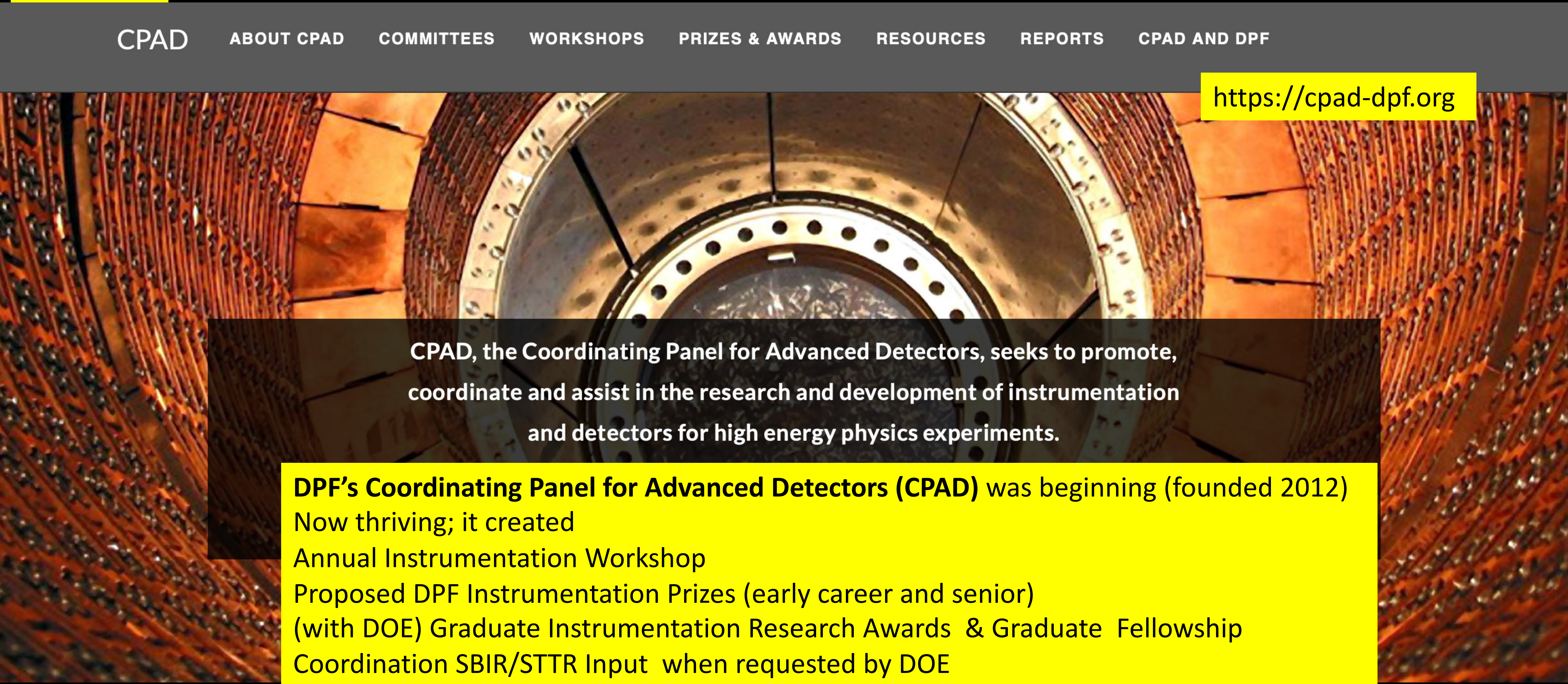
Miracle of FLASH therapy



Single ultra-high dose-rate ($\geq$ 40 Gy/s) radiotherapy reduces harm

Since last Snowmass

Instrumentation Frontier

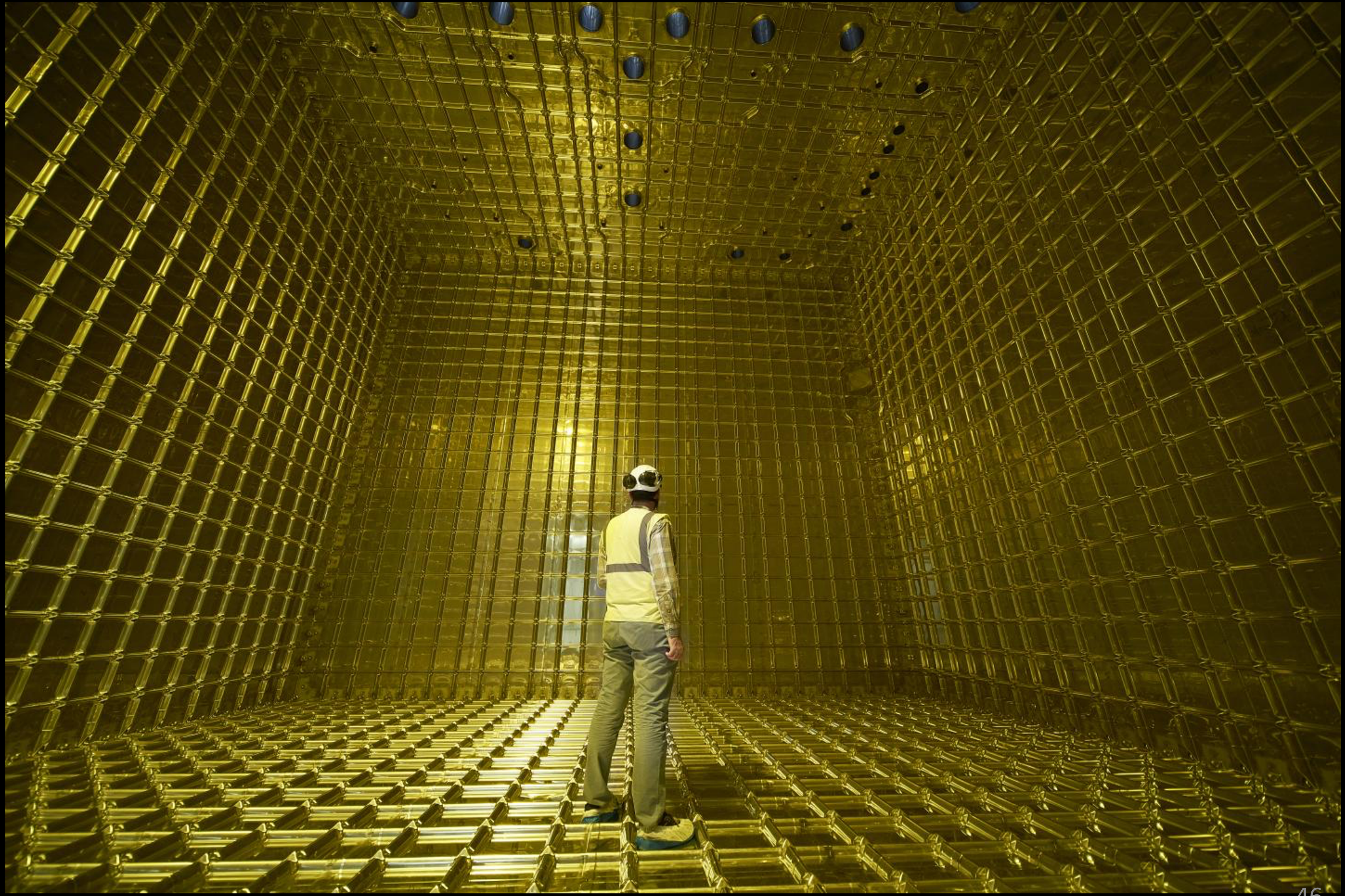


https://cpad-dpf.org

DPF's Coordinating Panel for Advanced Detectors (CPAD) was beginning (founded 2012)
Now thriving; it created
Annual Instrumentation Workshop
Proposed DPF Instrumentation Prizes (early career and senior)
(with DOE) Graduate Instrumentation Research Awards & Graduate Fellowship
Coordination SBIR/STTR Input when requested by DOE
Improved status and coordination of the US instrumentation community

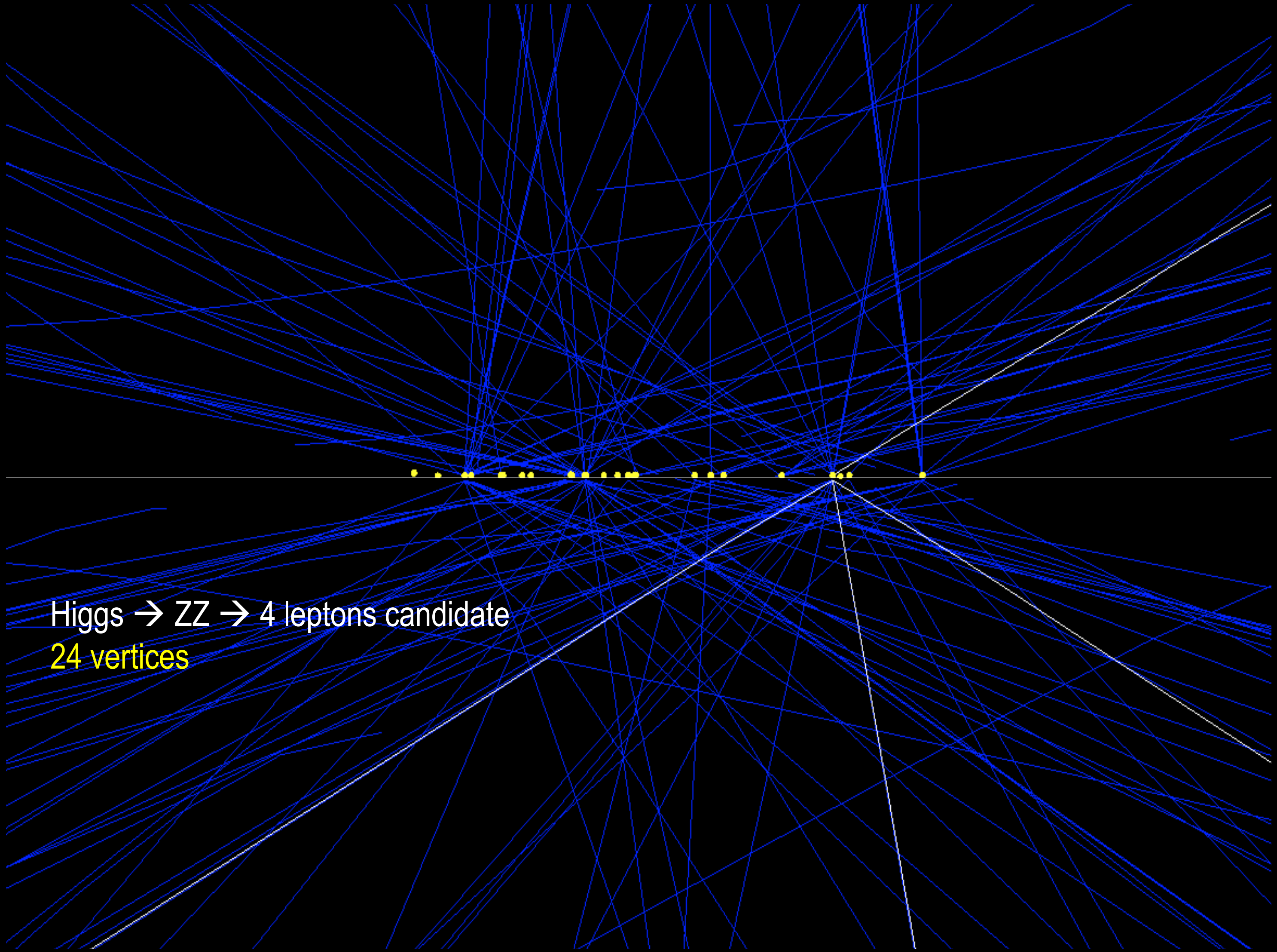
Proto-DUNE @ CERN

The key technologies for first DUNE FD have been demonstrated

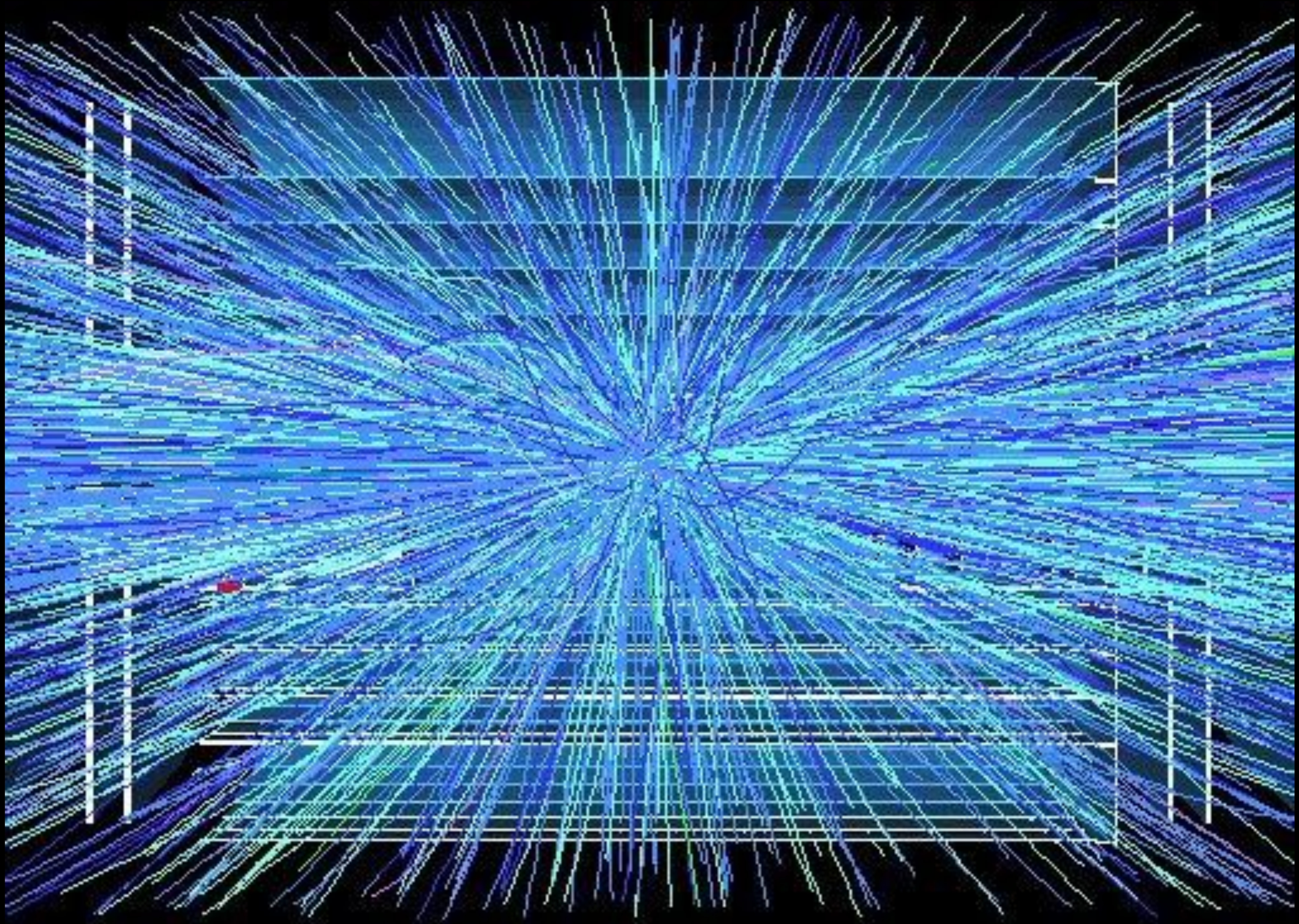


Since last Snowmass Exciting progress:

Collisions at the LHC



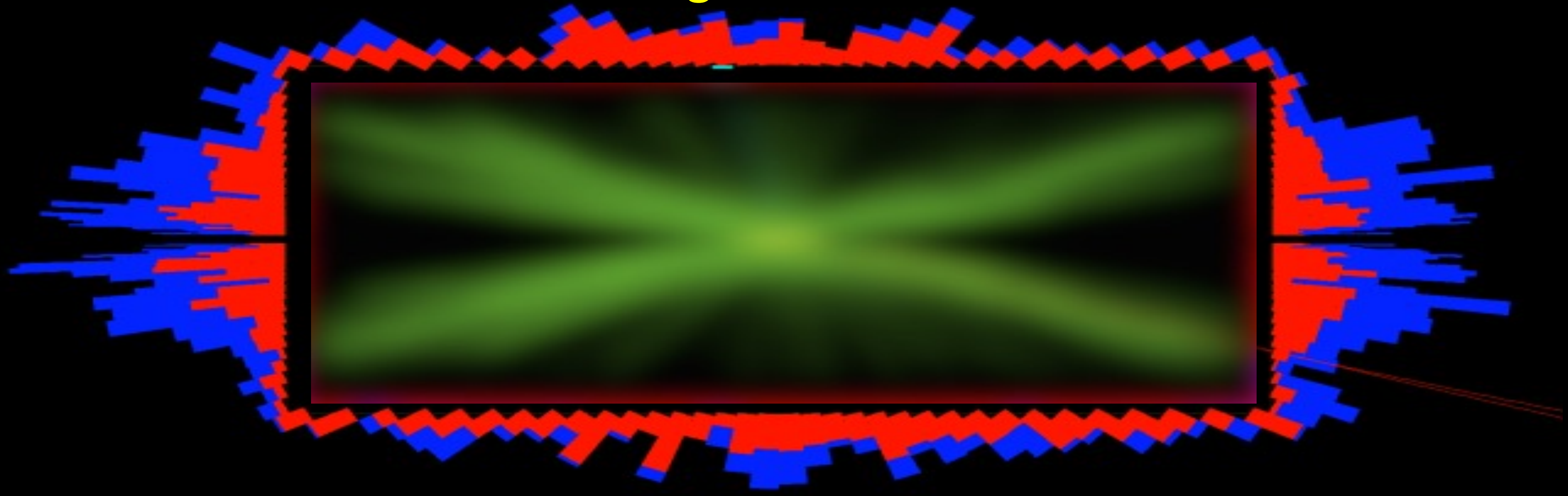
Collisions at the HL-LHC (~2029)



Event reconstruction challenges at HL-LHC

- High Luminosity → large data set, large pileup, high radiation dose

Viewing collisions in 3 D



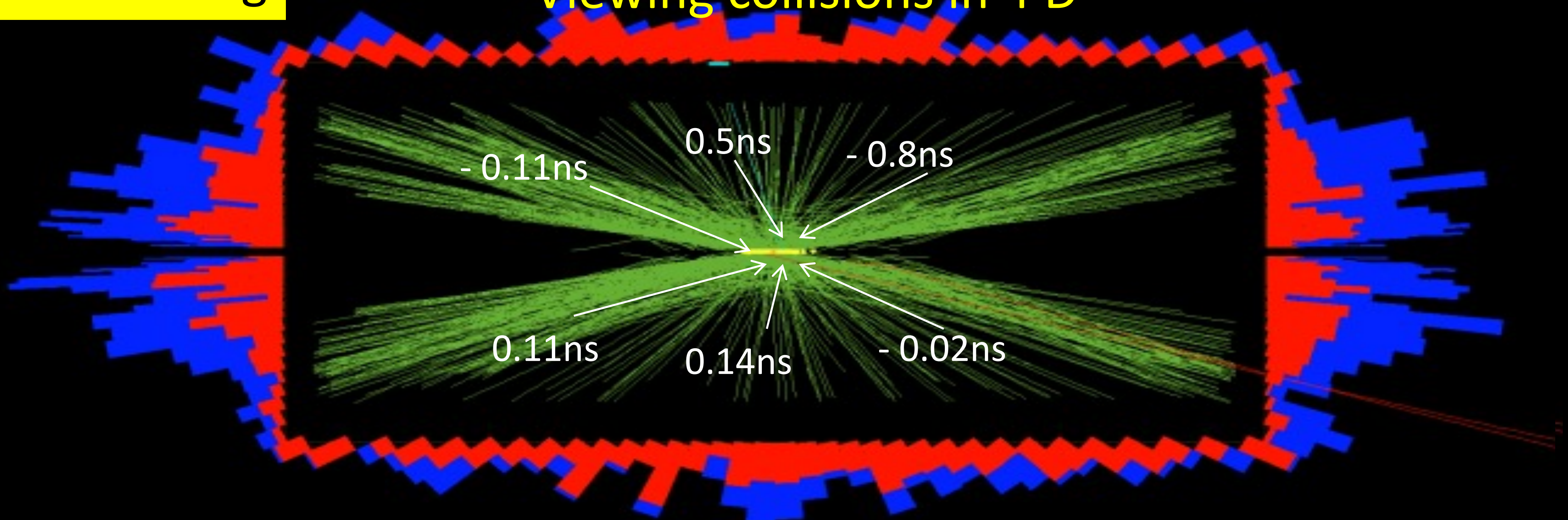
Since last Snowmass Exciting progress:

Event reconstruction challenges at HL-LHC

- High Luminosity → large data set, large pileup, high radiation dose

Precision Timing

Viewing collisions in 4 D

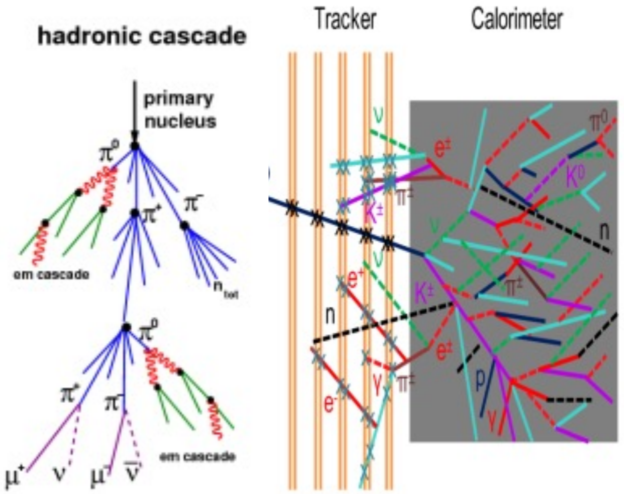


- For HL-LHC, this is enabled by new precision timing detectors → LGADs and SiPMTs
- Experience gained will be crucial for future high energy hadron colliders

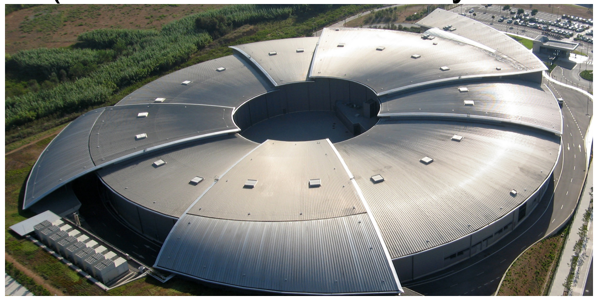
Since last Snowmass Exciting progress:

LGADs and timing multiple applications beyond HEP

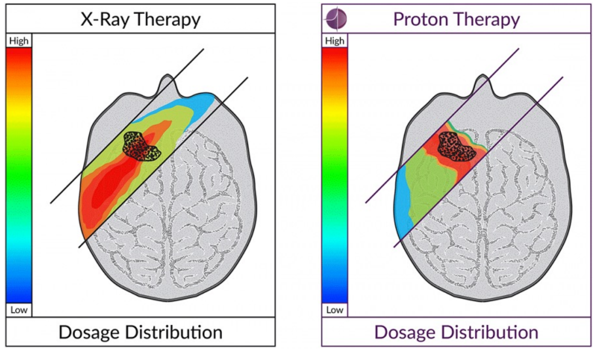
Space Applications
(Time resolved tracking)



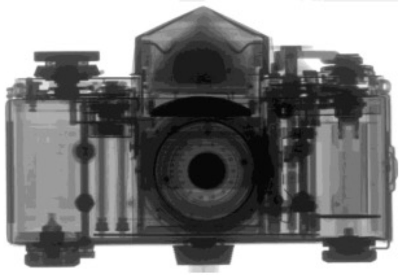
Synchrotron Applications
(LGAD tailored for X-ray detection)



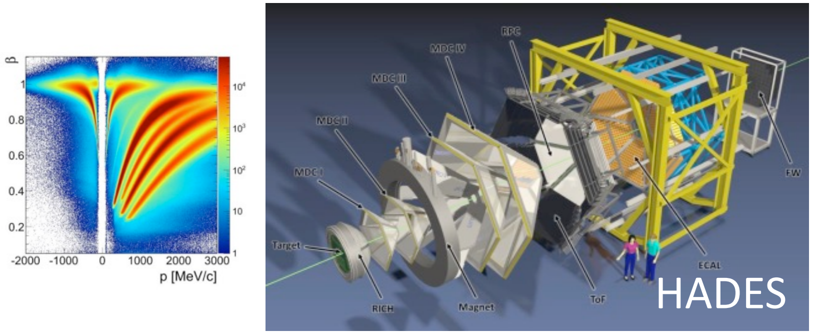
Medical Physics
(4D tracking, X-ray detection...)



Neutron Imaging
(Combining timing LGAD with a conversion layer)



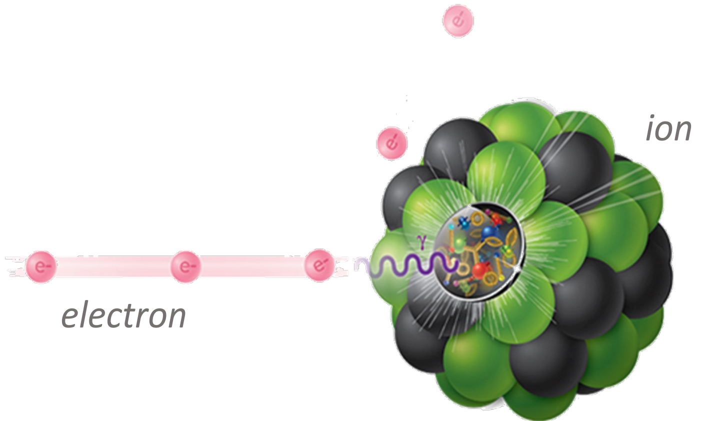
Nuclear Physics
(Particle identification)



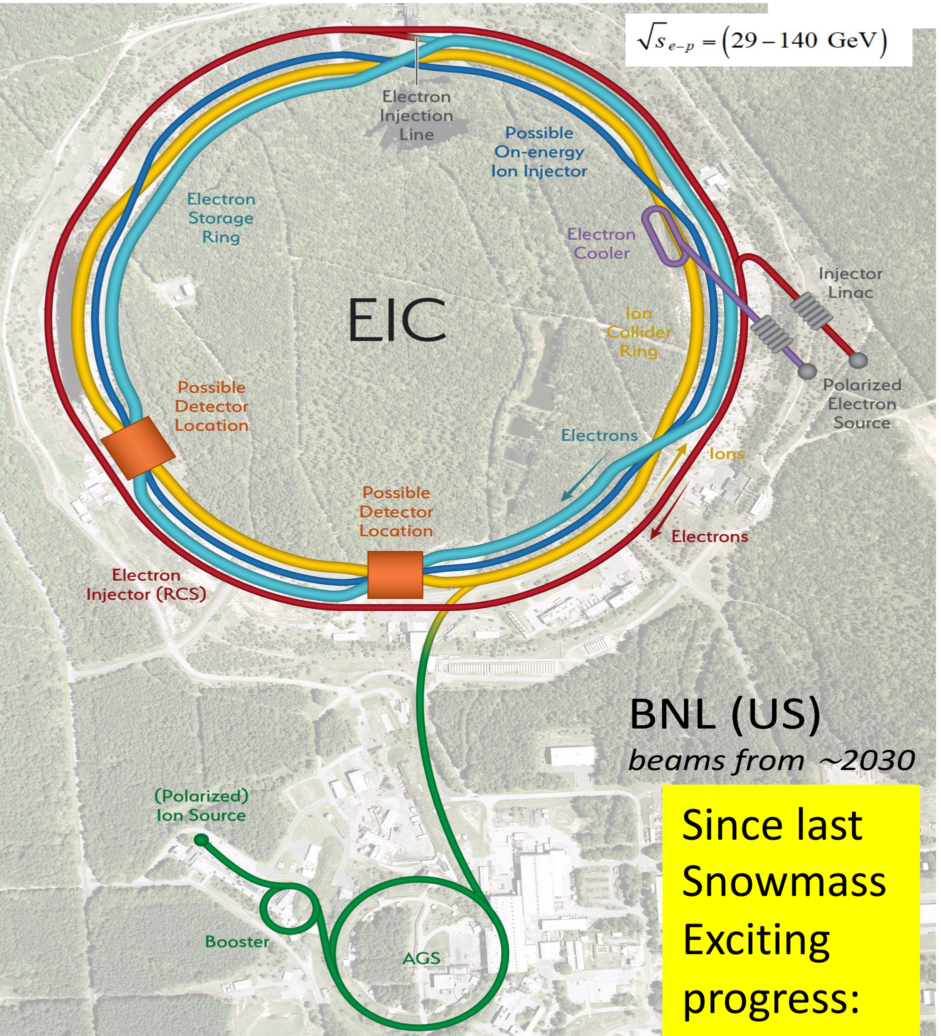
Details at various recent workshops:

RD50 Workshops
TREDi workshops
VERTEX
Vienna conference
Etc…

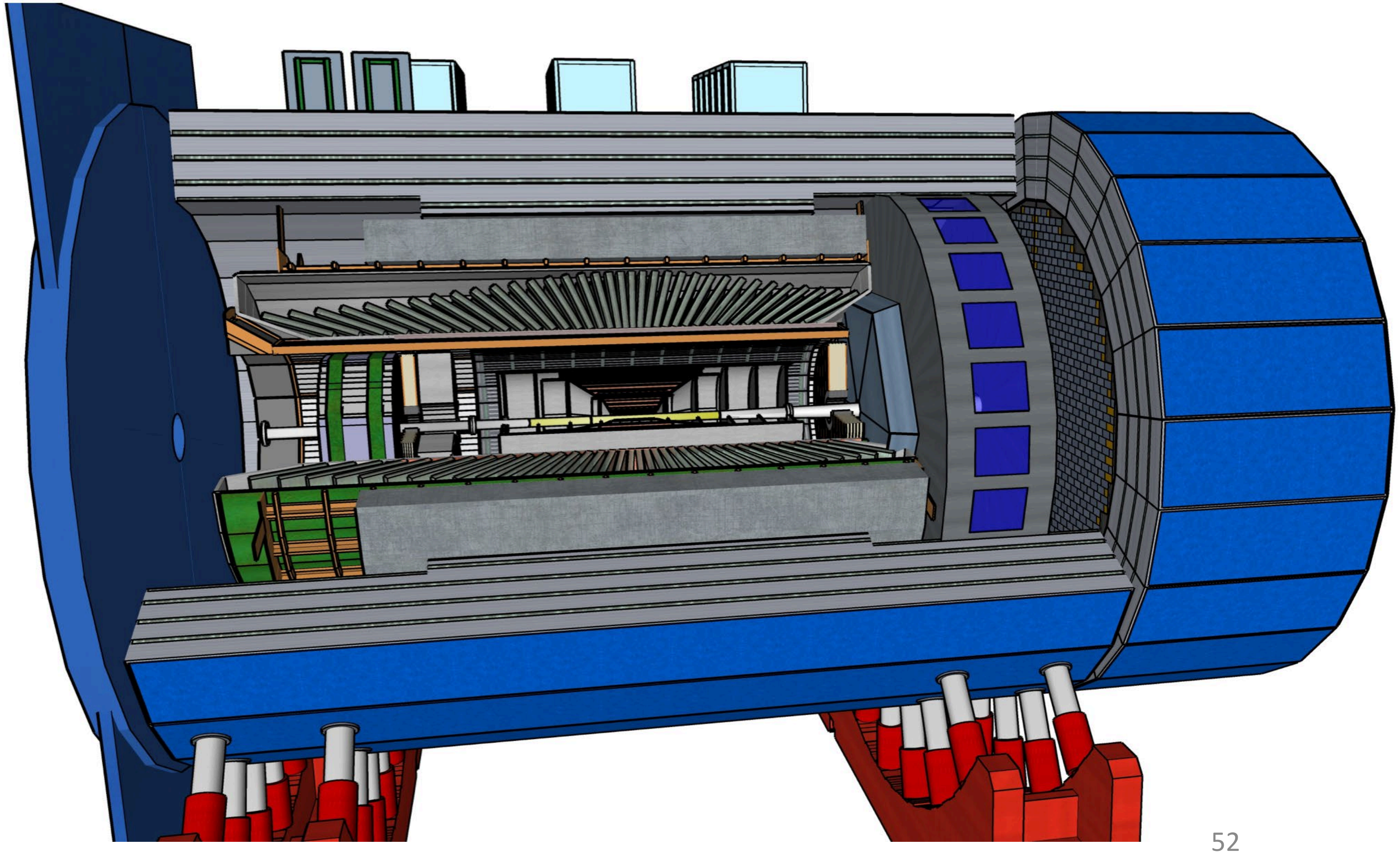
Electron Ion Collider @ BNL beams from ~2030 concurrent operations with HL-LHC for a decade & mutual interest to NP & PP



EIC Comprehensive Chromodynamics Experiment

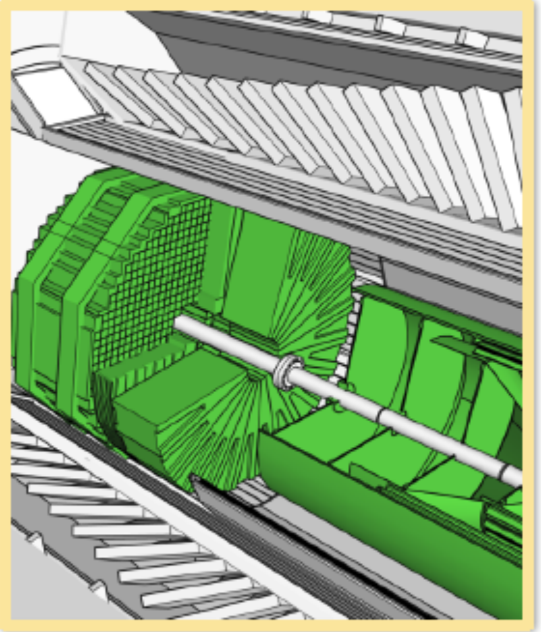


Since last Snowmass Exciting progress:



The ECCE Reference Technologies

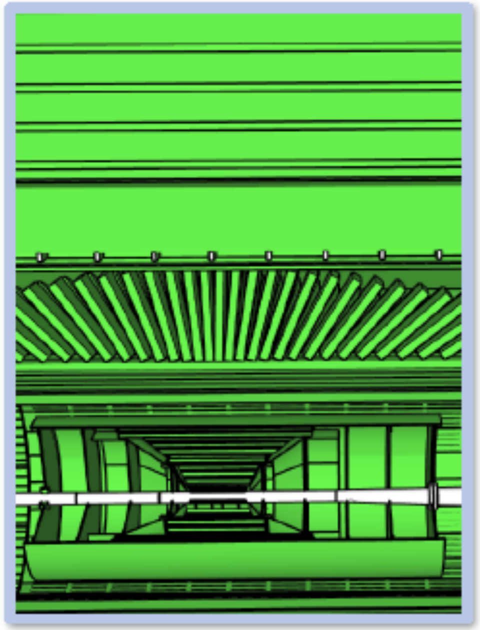
Most technologies in common with the LHC/HL-LHC & RHIC:
silicon, gaseous, photo, particle identification, calorimetry



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



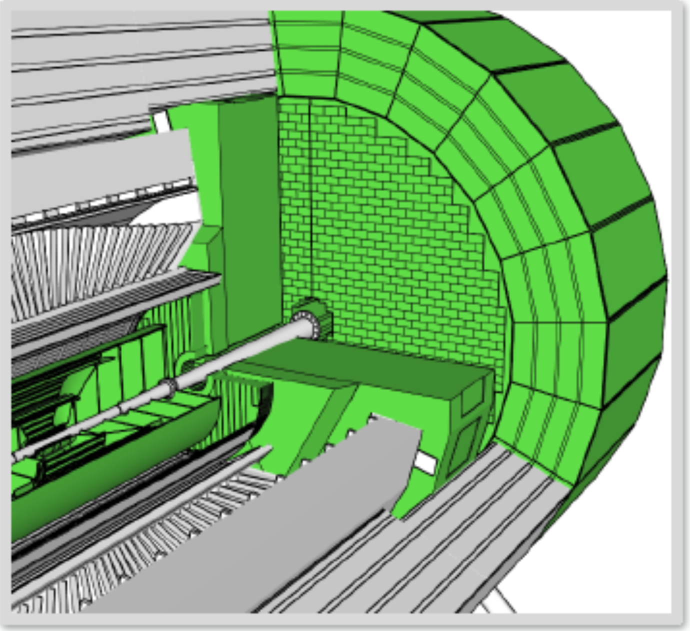
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:

NP & PP working side by side immensely synergistic

Since last Snowmass Exciting Progress. Quantum was not mentioned in 2013

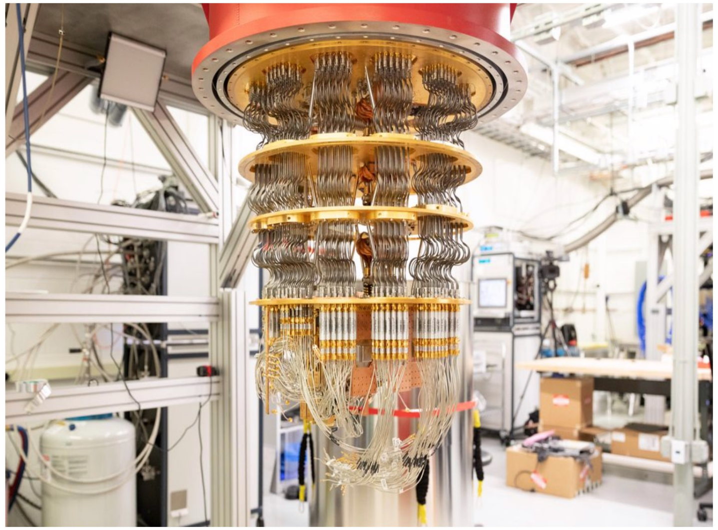
Quantum 2.0

The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

Google's quantum supremacy is only a first taste of a computing revolution

"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

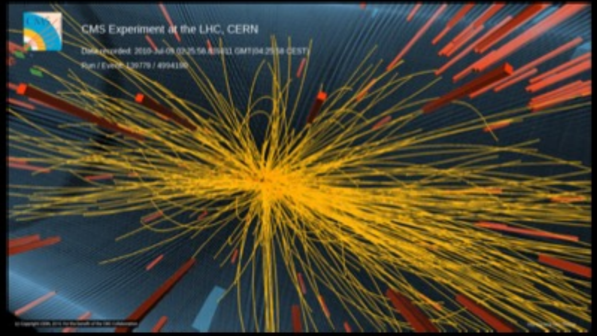
Stephen Shankland October 25, 2019 6:20 AM PDT



One of five Google quantum computers at a lab near Santa Barbara, California.

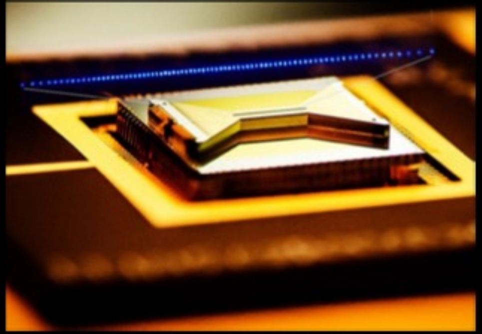
Stephen Shankland/CNET

AI, ML on Quantum annealer



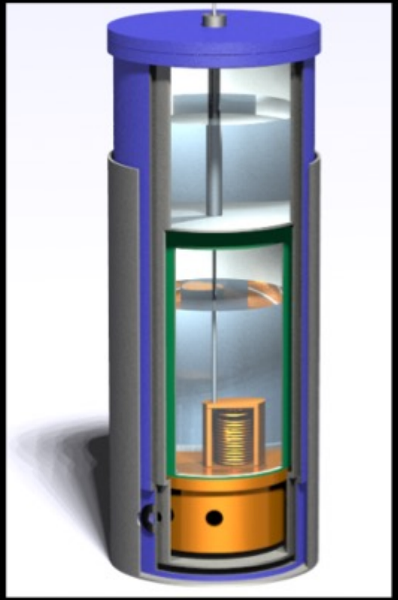
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks

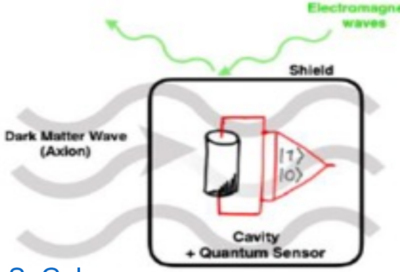


Nature (564) 87 (2018)

Quantum and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US (DOE QuantISED UK QTFP…)

QUANTUM TECHNOLOGY INITIATIVE

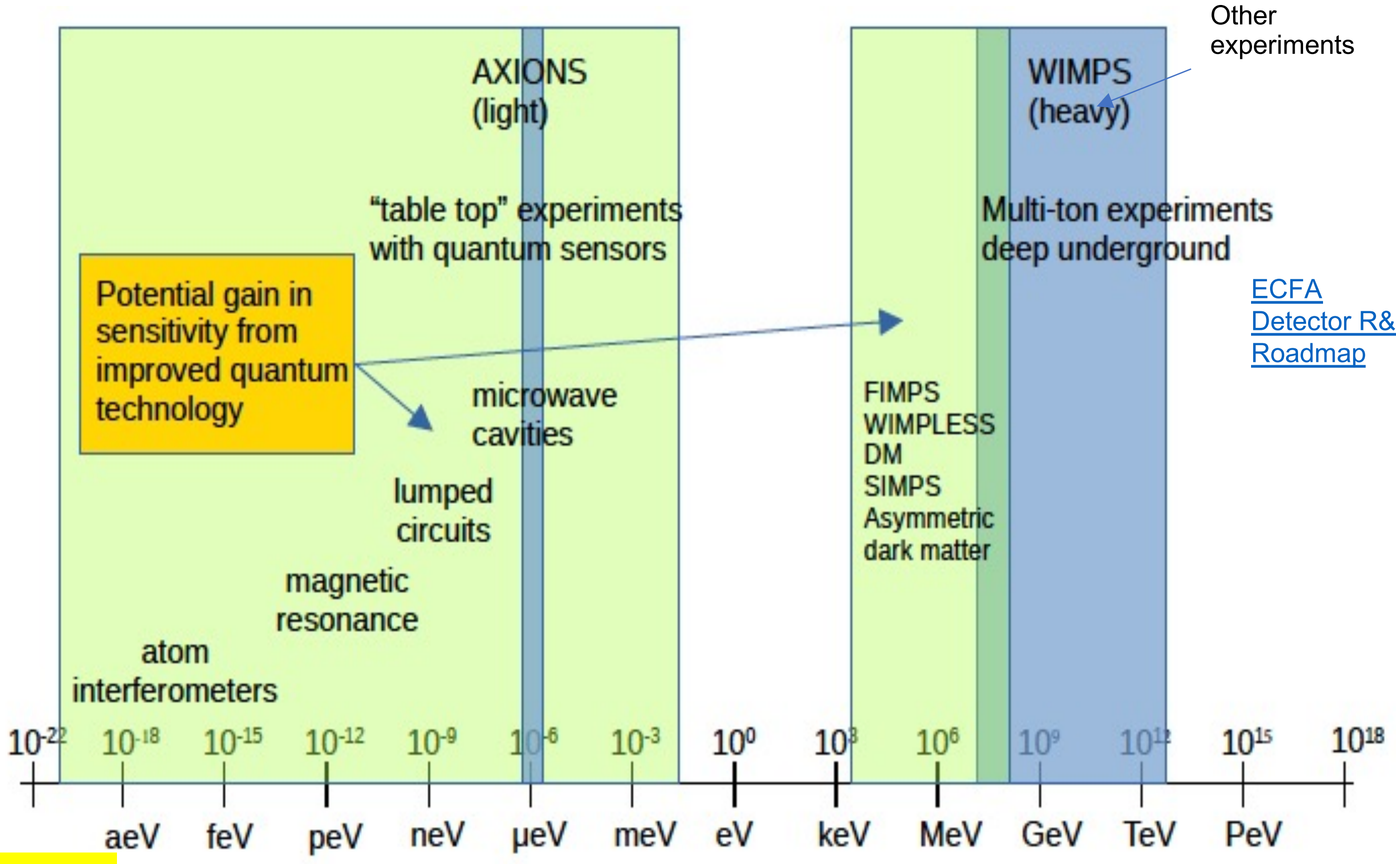


S. Golawa

Microwave Cavity

Significant new funding for HEP & spectacular opportunities for interdisciplinary collaboration

Example: potential mass ranges that quantum sensing approaches open up for Axion searches



Axion mass range

ECFA Detector R&D Roadmap

Blue: now
Light green: with quantum

Last P5 Recommendations

Recommendation 27: Focus resources toward directed instrumentation R&D in the near-term for high-priority projects. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D.

Did not yet happen
We need to do better

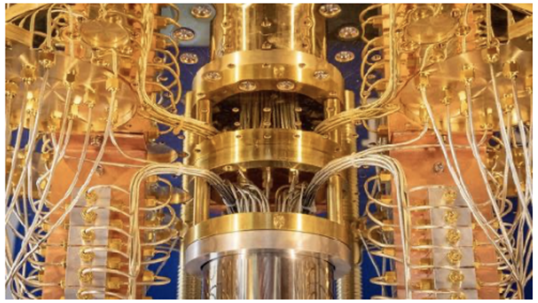
Recommendation 28: Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities. Encourage graduate programs with a focus on instrumentation education at HEP supported universities and laboratories, and fully exploit the unique capabilities and facilities offered at each.

Since last Snowmass Exciting Progress. AI/ML Much less Prominent in 2013

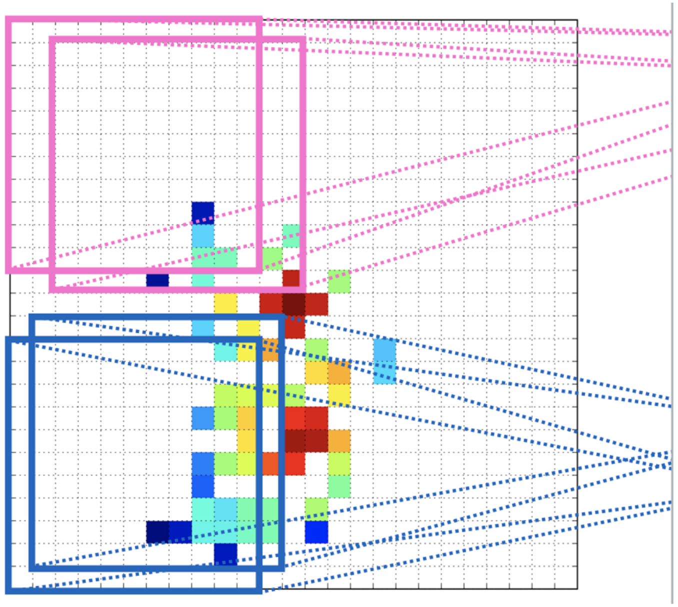
Future of Software and Computing (S&C) in HEP

S&C technologies are changing the way we do HEP science

- Trend towards computing hardware heterogeneity and specialization, and increased use of high-performance computing facilities
- AI/ML not on the horizon in 2013, **now widespread in every HEP area**
- Quantum computing is entering the stage with potential impact on quantum many-body systems, event generators, data analysis, etc.



Stephen Shankland/CNET

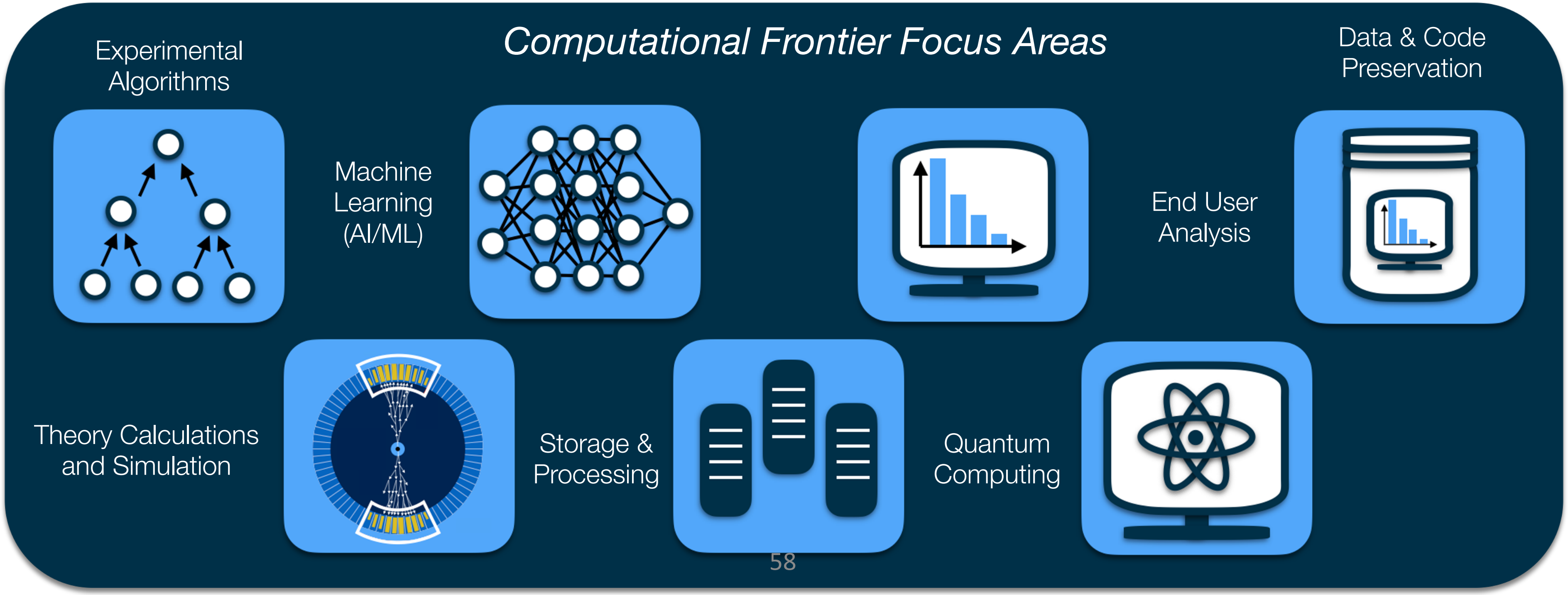


Convolutional neural network applied to a jet represented as an image.

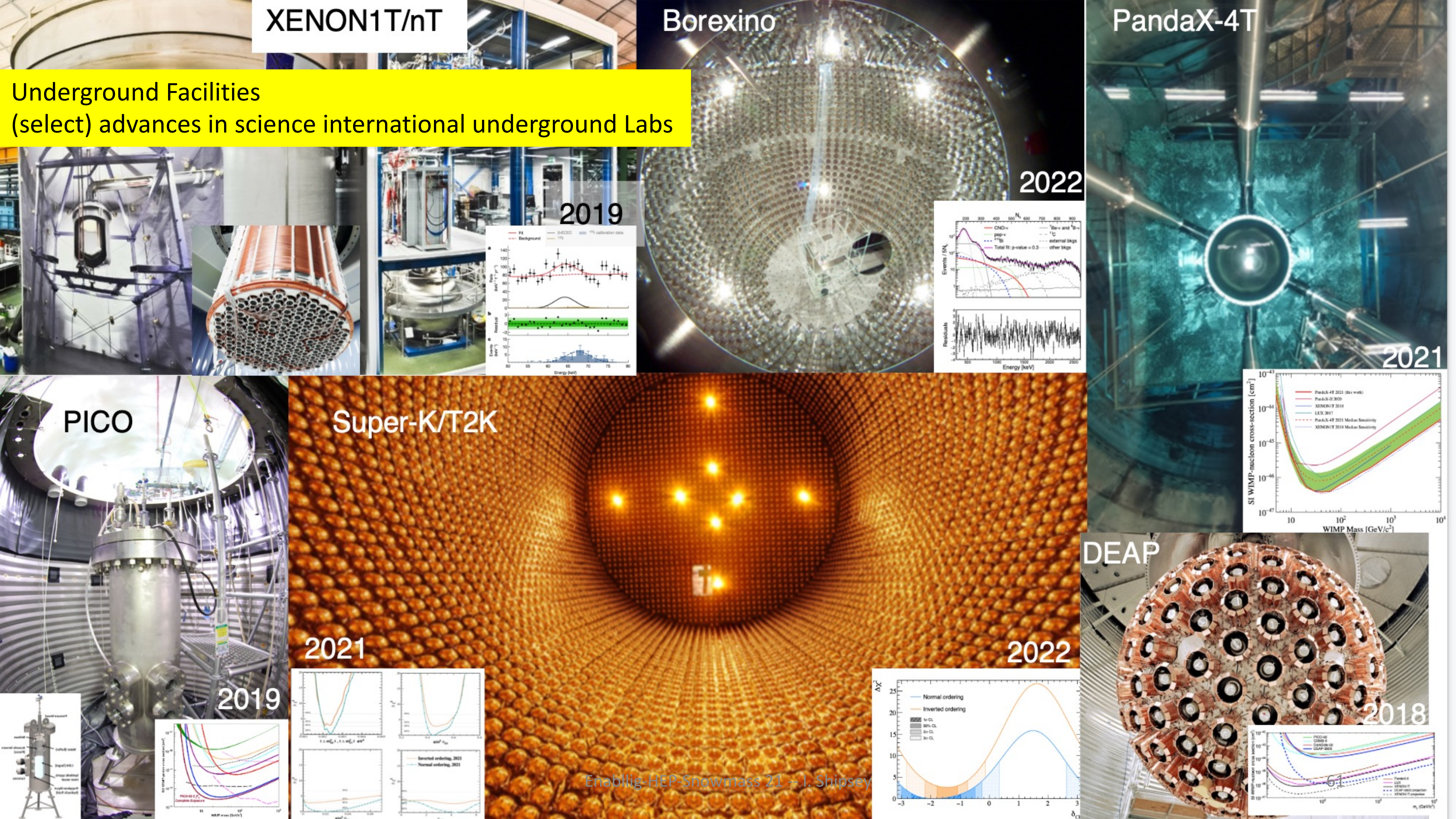
Future of Software and Computing (S&C) in HEP

Computing is essential to all experiments and many theoretical studies

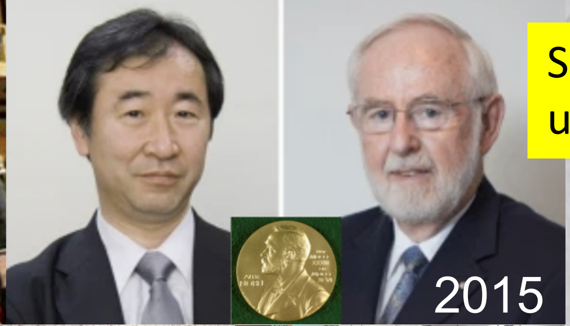
- Data volumes, detector complexity, precision required in calculations and simulation will continue to grow in near- and far-future experiments and surveys
- Size and complexity of the S&C is **commensurate with that of the experimental instruments**; projects may also need software-detector codesign
- S&C changes on a faster timescale than facilities, experiments, and surveys. Perhaps need an entity that can continuously promote, coordinate, and assist on S&C needs. A CPAD for S&C?

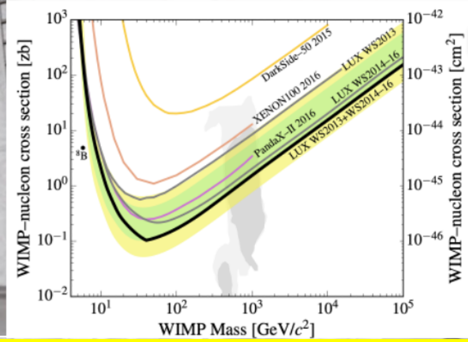


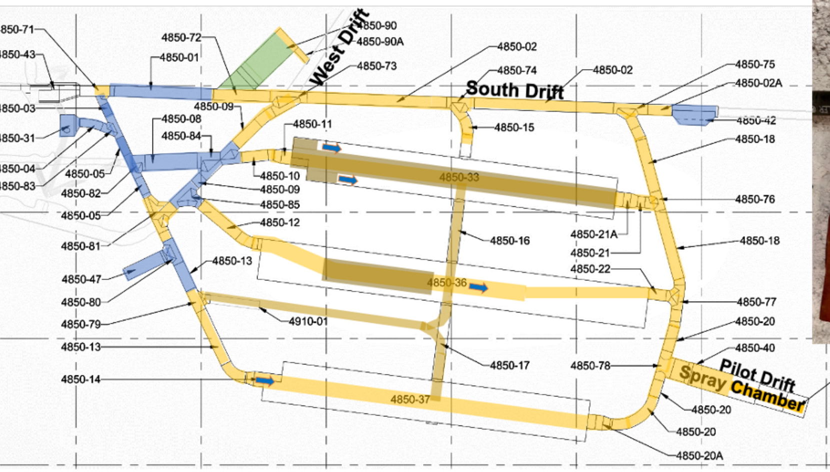
Underground Facilities
(select) advances in science international underground Labs



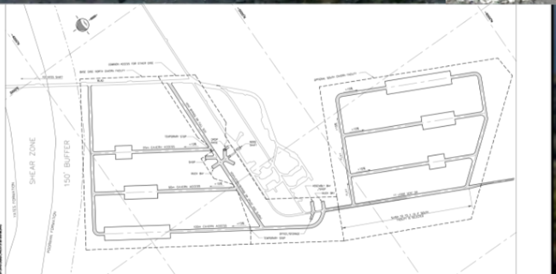
Snowmass 2013 DUSEL had been cancelled- future of US underground science was uncertain at best.

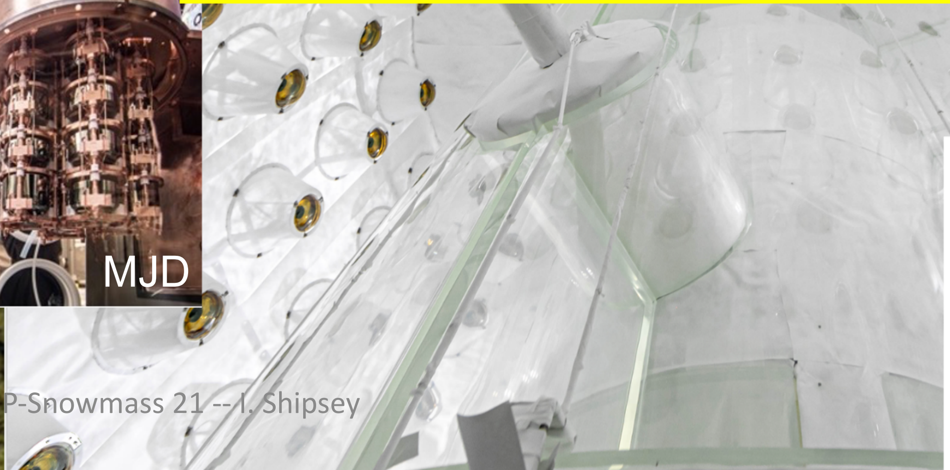


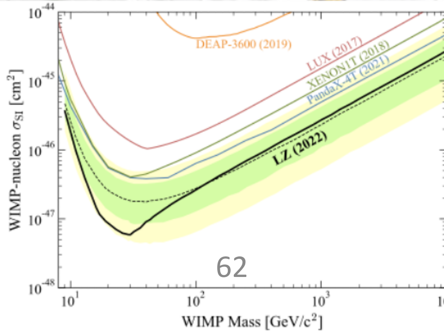




Now: SURF world-leading, multidisciplinary facility, 2 generations of world-leading Dark Matter experiments, excavation for DUNE & a haven for international underground science in physics, biology, geology, engineering.







Theory is essential

The US lags Europe in its support for the theory community
it is important to address this

European Strategy Update

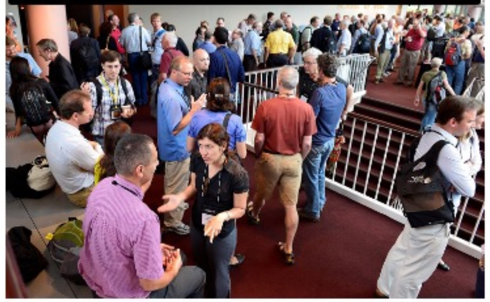
4

Other essential scientific activities for particle physics

B. Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. ***Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.***

- **Community Engagement** interacting with connected communities is of fundamental importance

within HEP



with industry

with education

with policy

with society

Community Engagement Frontier the work over the next decade to improve, develop, and expand Community Engagement
→ make HEP stronger and healthier,
→ achieve the physics vision Snowmass 2021 will help define

Snowmass 2013

- Communication, Education & Outreach

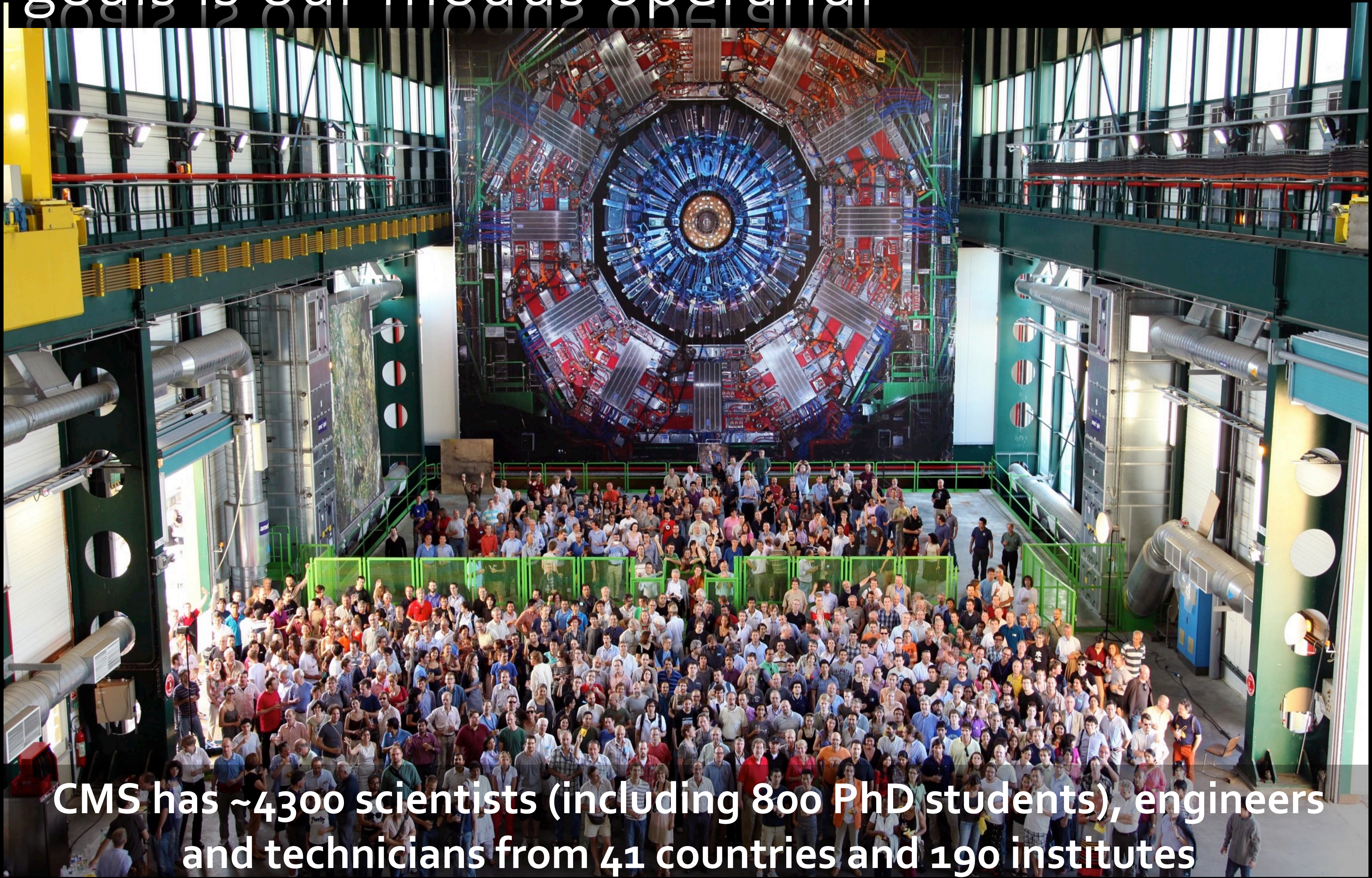
Snowmass 2021: CEF

- Applications & Industry
- Career Pipeline & Development
- Diversity, Equity & Inclusion
- Physics Education
- Public Education & Outreach
- Public Policy & Government Engagement
- Environmental & Societal Impacts

Particle Physics is Global

- The regions can together address the full breadth of the field's most urgent scientific questions each hosting unique world-class facilities at home and partnering in high-priority facilities hosted elsewhere.
  - Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a continued global vision.

Working together to achieve scientific goals is our modus operandi



CMS has ~4300 scientists (including 800 PhD students), engineers and technicians from 41 countries and 190 institutes

Working together to achieve scientific goals is our modus operandi

Our international collaborations inspire, made up of myriad individuals with diverse interests working together to achieve scientific goals

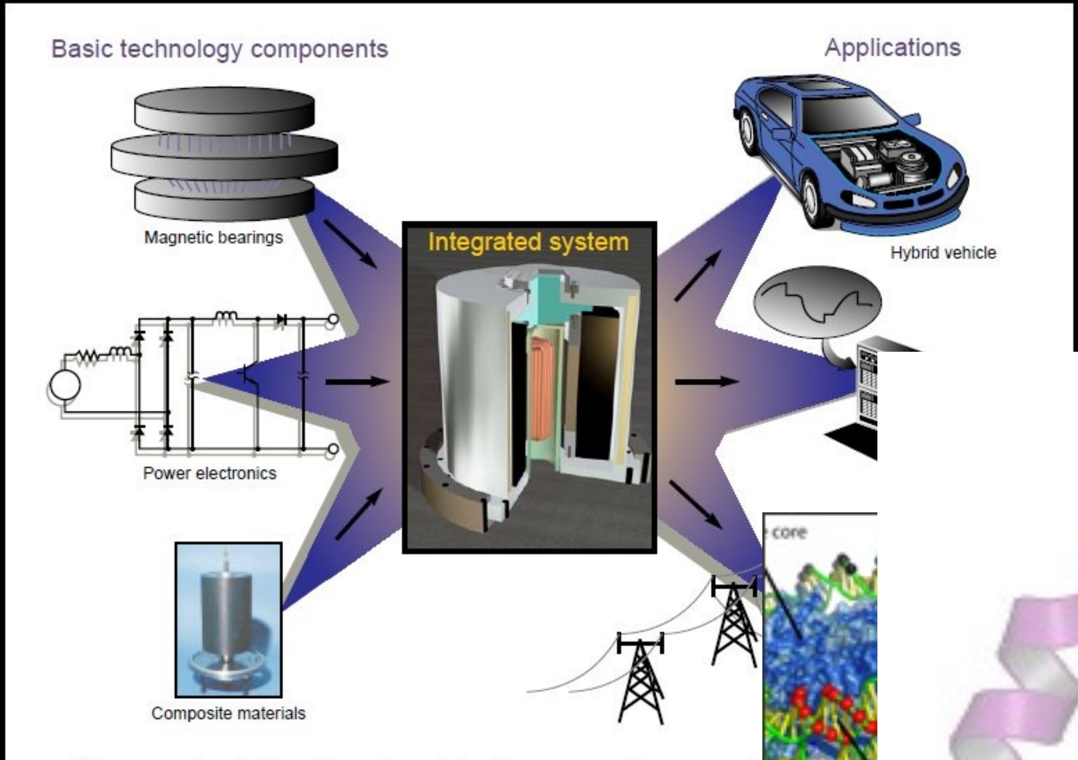
CMS has ~4300 scientists (including 800 PhD students), engineers and technicians from 41 countries and 190 institutes

To achieve the vision for our field
We must be united in our aspirations one field with one voice

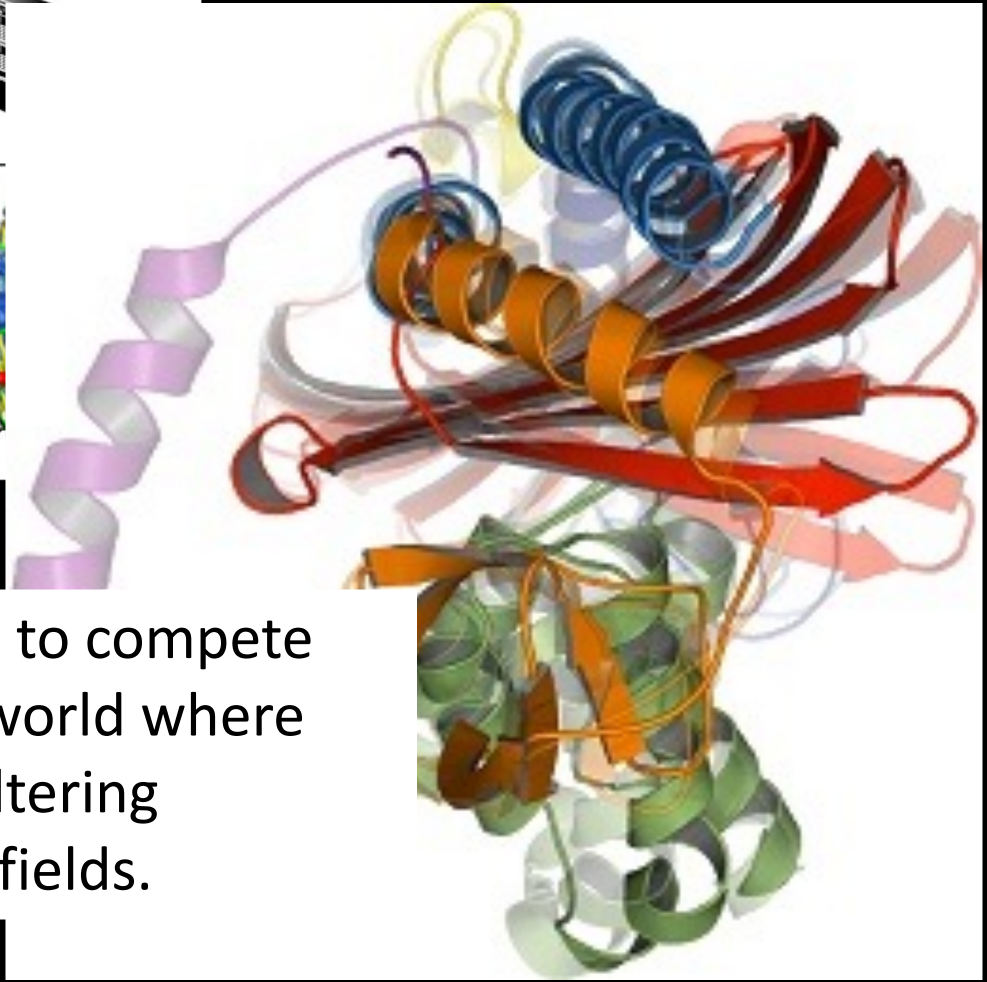
The only enemies you have are those you have not spoken to (paraphrase) *Henry Wadsworth Longfellow*

The only enemies you have are those you have not spoken to (paraphrase) *Henry Wadsworth Longfellow*

The Snowmass process is giving us a renewed & deeper appreciation of each other’s science



Concept of the flywheel battery system and



Our science is compelling enough to compete favorably for the best talent in a world where transformational and paradigm-altering advances are happening in other fields.

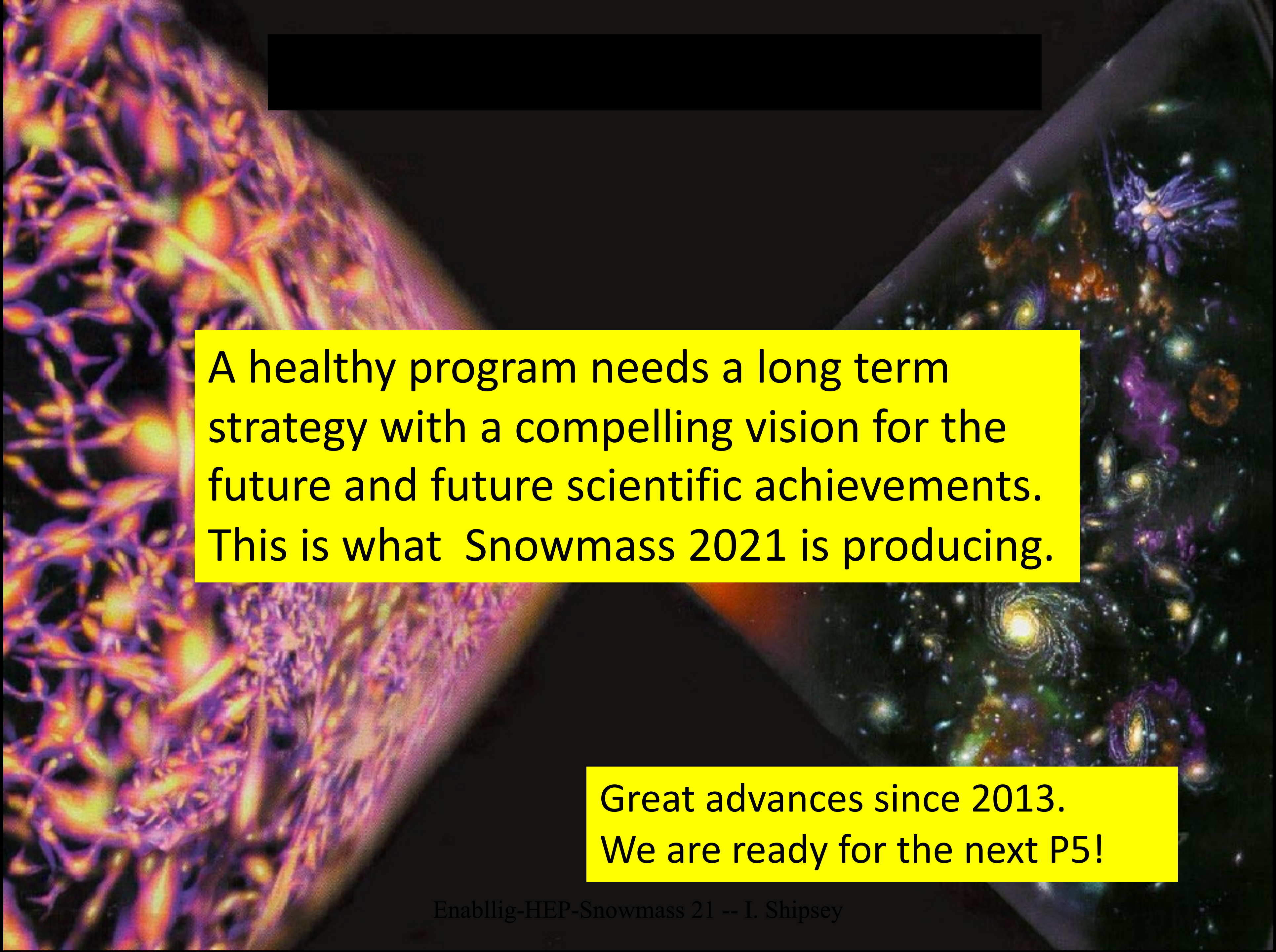
There is no entitlement for particle physics funding.

We must compete favorably with other opportunities on all the playing fields: in the agencies in Congress

and in academia.

We see our science as compelling and we need to convince others it is compelling as well.

[redacted]



A healthy program needs a long term strategy with a compelling vision for the future and future scientific achievements. This is what Snowmass 2021 is producing.

Great advances since 2013.
We are ready for the next P5!

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

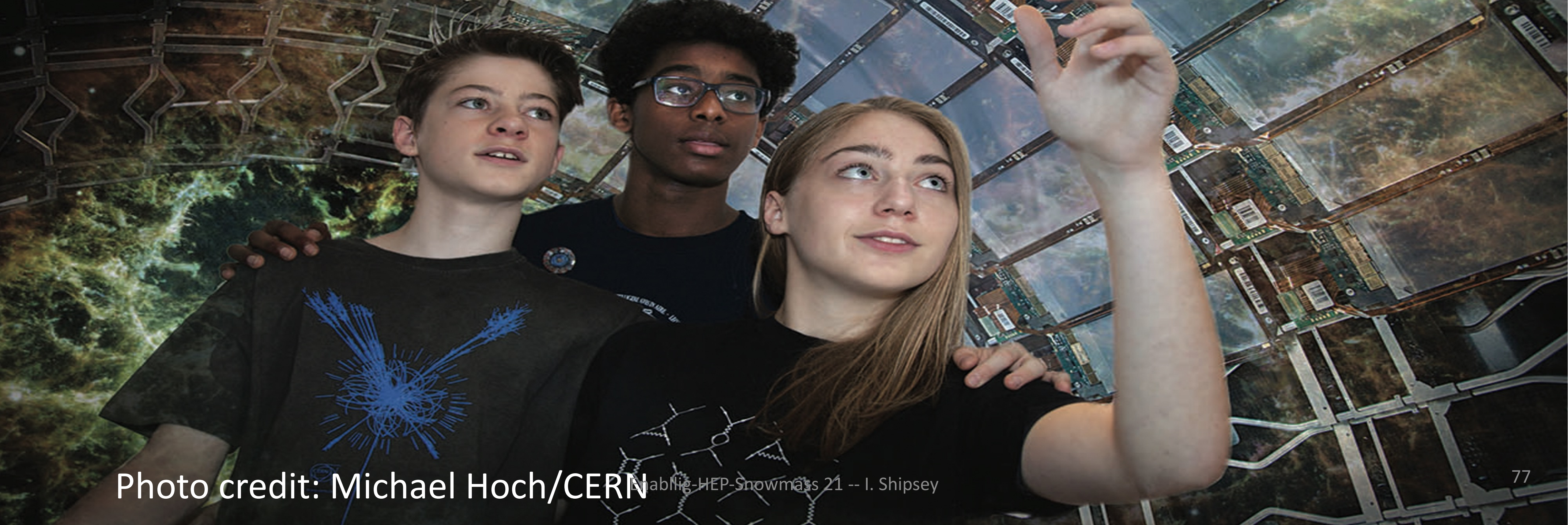


Photo credit: Michael Hoch/CERN

Accelerators, community engagement, computational, instrumentation, theory, underground

Each Frontier describes briefly

a) their goals and priorities;

b) critical R&D or infrastructure needed during 2025-2035 to support and enable the physics vision discussed during the panel on physics highlights and how they may benefit from targeted funding;

c) R&D or infrastructure needs to support the proposed physics measurements in 2035+ and may be developed by next P5.

Each Frontier will comment on the related P5 science drivers and also if any of their goals do not map on the P5 science drivers.

- 10:30 AM — **Accelerator Frontier**
  Speaker: Steve Gourlay (LBNL)
  AF_Panel2_5slides....
- 10:40 AM — **Community Engagement Frontier**
  Speaker: Breese Quinn (University of Mississippi
  CEF_Panel_2.pdf
- 10:50 AM — **Computational Frontier**
  Speaker: Daniel Elvira (Fermilab)
  CompF-Panel4-V5....
- 11:00 AM — **Inrstrumentation Frontier**
  Speaker: Petra Merkel (Fermi National Accelerat
  IF-Concluding-Plen...
- 11:10 AM — **Theory Frontier**
  Speaker: Nathaniel Craig (UC Santa Barbara)
  CSS TF Panel 2.pdf
- 11:20 AM — **Underground Facilities Frontier**
  Speaker: Jeter Hall (SNOLAB)
  UF-Summary Panel...